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# ORIGIN OF THE EARTH AND PLANETS

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# INTRODUCTION

Cosmogony—the branch of knowledge dealing with the origin and evolution of the celestial bodies—is of enormous importance for natural science.

Ever since ancient times man has always wanted to know how the Earth—the cosmic body on the surface of which he lives—originated and evolved. The question is of great practical import, being one of the basic problems of geophysics, geochemistry and geology. Without knowing how the Earth originated, one can neither understand its evolution nor, consequently, have a correct idea of its internal structure or of the processes taking place in it. Cosmogony is extremely important in the elaboration of a correct materialist world outlook.

The Earth is not an isolated cosmic body, it is one of the planets of the solar system. A number of features in the structure of the planetary system indicate that the planets originated simultaneously during the evolution of a uniform material medium. These features serve as the guiding thread in tackling the problem of the origin of the Earth and the other planets.

In examining the origin not only of the Earth, but of a whole system of bodies, the investigator deals with a far wider range of factual material, which, naturally, complicates his work. But only thus can he establish the actual process of the evolution of the Earth and the planets.

The investigator must first systematize the wealth of facts concerning the structure of the Earth, planets, asteroids, comets and meteorites, and the structure of the system as

a whole. He must select the main facts and through analyzing them establish, in rough outline, the original state of the substance now forming the Earth and the other bodies of the solar system. This in turn will enable him to analyze the process of its development and, by comparing the results of his analysis with the other, as yet unexamined properties of the present-day solar system, define more precisely the previous state and subsequent evolution of this substance.

Thus, by investigating the ever-increasing factual data, repeatedly passing from analysis of the present properties and conjectures about their origin to analysis of the processes of the evolution of the surmised original state of the substance and discarding erroneous and clarifying the correct assumptions, the investigator will advance towards a correct theory of the origin and evolution of the Earth and the planets.

The investigator must examine the facts with a very critical eye. Only limited evidence about the structure of the Earth and other bodies of the solar system has been obtained by direct observation and measurement. Much was obtained by interpreting and generalizing observation data, when, together with applying incontestable scientific laws and propositions, recourse was had to supplementary hypotheses and when surmises concerning the formative processes of the bodies under investigation were applied tentatively. After several decades, the conditional character of these data was forgotten and they began to be regarded as axiomatic. A few years ago, for instance, the idea that the Earth had an iron core was held to be incontrovertible. And yet it was only a hypothesis, closely associated with the conjectures about the Earth's initial molten state.

It would be wrong to expect from an investigator engaged in planetary cosmogony an explanation of *all* the data about the Earth, planets and other bodies. Among these data there are those that relate to the peculiarities of the evolution of the given body or even part of it. In explaining the essential facts, theory should not resort to artificial

hypotheses or refer to natural laws not yet discovered by science. The incongruencies with the principal data will show that the investigator, by confining himself to the separate facts that caught his attention, has gone the wrong way about things. As a result, instead of clarifying the actual process of evolution, he indicated a process that, while generally possible, was out of the question in the given case, judging by the incongruencies.

Elucidation from a single point of departure of the basic structural features of the solar system, of the structure and evolution of the Earth and the other celestial bodies, is the goal of the scientists engaged in planetary cosmogony. Soviet science is successfully advancing towards this objective. In recent years, thanks to the efforts of Academician Otto Schmidt (1892-1956), renowned Soviet scientist and Polar explorer, and the group of scientists he led till his death, the foundations have been laid of a theory concerning the origin of the Earth and the planets. This theory, together with the closely related problems of the Earth's internal constitution and evolution, is the subject of the present book.*

## I THE STRUCTURE OF THE SOLAR SYSTEM

The solar system consists of a central body, the Sun, around which numerous satellites revolve. The latter are very small compared with the Sun, but in terms of terrestrial scales some of them are very large. Among the largest of the satellites are the nine major planets, including our Earth. Then there are the thousands of asteroids (minor planets) and comets, and the enormous swarms of minute bodies and particles. Moving within the solar system these particles sometimes collide with the Earth. Diving into the Earth's atmosphere at tremendous speeds, they produce the flash of a meteor—the "shooting star." Sometimes large

* See also Otto Schmidt, *A Theory of Earth's Origin. Four Lectures*

meteoric bodies do not evaporate fully in the air, with the result that parts of them fall on the Earth's surface in the form of meteorites.

The motion of the planets around the Sun is characterized by a number of regularities.

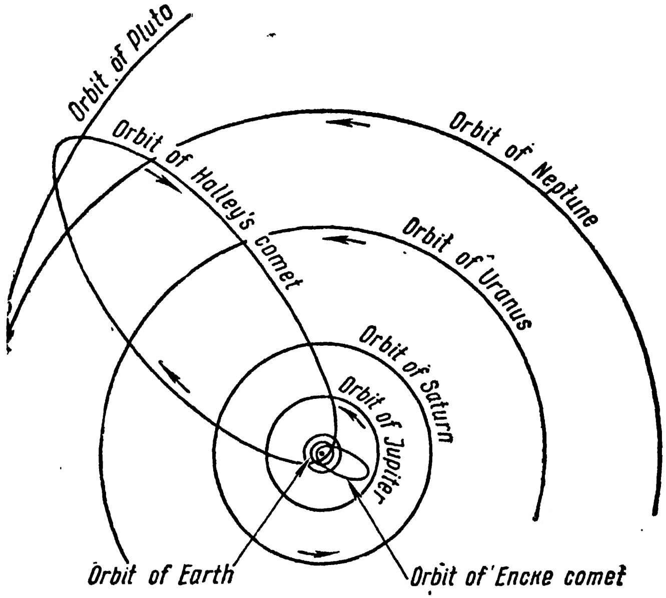


*Fig. 1.* Diagram of the solar system. Orbits of Mercury and Venus are not shown

First, the orbits of the planets are well-nigh circular, barely extended ellipses (Fig. 1.). Incidentally, both the stellar and our solar systems provide numerous instances of movements of bodies along highly extended paths (e.g., comets).

Secondly, the planetary orbits around the Sun are little inclined to one another, and therefore the planetary system is an exceedingly flat formation (Fig. 2).

*Fig. 2.* The solar system in space

Thirdly, all planets, without exception, major and minor, revolve around the Sun in one and the same direction. A view of the solar system from a position high above the North Pole would show that the planets move counter-clockwise. The planets themselves (save Uranus*), and the Sun, rotate on their axes in the same direction, i.e., counter-clockwise. Furthermore, the bulk of the satellites of the planets revolve around their primaries also counter-clockwise.

These regularities indicate that the planetary system is not an accidental conglomeration of bodies, each of different origin, but a single family of planets which originated at one and the same time and place.

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* Uranus rotates as if "lying on its side." Its axis of rotation is inclined only 8° towards the orbital plane, so that Uranus' North Pole is tilted away 98° from the perpendicular to the orbital plane (Fig. 3). Since this inclination exceeds 90°, Uranus' motion is formally regarded as retrograde.

This is also borne out by the connection between the physical properties of the planets and their place in the solar system.

The four planets nearest to the Sun—Mercury, Venus, the Earth and Mars—are comparatively small (the Earth being the largest), but of a rather great density, four or five times the density of water. The distant planets—Jupiter, Saturn, Uranus and Neptune—while much more massive and much larger than the terrestrial planets, have a

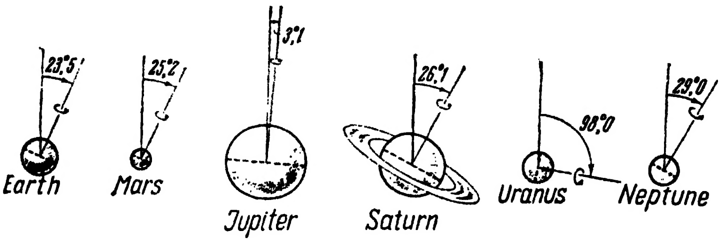



*Fig. 3.* Inclination of planetary axis of rotation with regard to the orbital plane of each planet

small mean density, approaching that of water (with Saturn's even less).

Compression of matter in the interior of the giant planets is greater than in the terrestrial planets. Nonetheless, their density is less than that of the terrestrial planets. It follows, therefore, that they consist of a different, lighter substance.

Beyond the major planets, there is another small one, Pluto, discovered in 1930. Since Pluto is very far away, we have but an extremely rough idea of its dimensions and mass.

The main facts about the planets and their orbits are given in Table 1.

A glance at the table, and also at Fig. 1, shows that the distances between neighbouring orbits increase with the distance from the Sun. This is also one of the regularities of planetary motion.

## Main Data on Planets and Their Orbits

| Name of planet | Mean distance from Sun in A. U.* | Eccentricity of orbit | Inclination of orbit to main plane | Mass of planet | | Planet radius (Radius of Earth=1) | Density in gr cm | Axial rotation | Number of satellites |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Mass of Sun=1 | Mass of Earth=1 | | | | |
| Mercury | 0.39 | 0.206 | 6.3 | $\frac{1}{6120000}$ | 0.0545 | 0.38 | 5.5 | $88^d$ | 0 |
| Venus | 0.72 | 0.007 | 2.2 | $\frac{1}{408600}$ | 0.816 | 0.96 | 5.1 | $20^d$? | 0 |
| Earth | 1.00 | 0.017 | 1.6 | $\frac{1}{333420}$ | 1.000 | 1.000 | 5.516 | $23^h\ 56^m\ 04^s$ | 1 |
| Mars | 1.52 | 0.093 | 1.7 | $\frac{1}{3110000}$ | 0.107 | 0.53 | 3.9 | $24^h\ 37^m\ 23^s$ | 2 |
| Jupiter | 5.20 | 0.048 | 1.3 | $\frac{1}{1047.4}$ | 318.35 | 10.95 | 1.34 | from $9^h\ 50^m$ to $9^h\ 56^m$ | 12 |
| Saturn | 9.54 | 0.056 | 0.9 | $\frac{1}{3499}$ | 95.33 | 9.14 | 0.70 | from $10^h\ 14^m$ to $10^h\ 38^m$ | 9 |
| Uranus | 19.19 | 0.047 | 1.0 | $\frac{1}{22870}$ | 14.58 | 3.90 | 1.4 | $10^h\ 42^m$ | 5 |
| Neptune | 30.07 | 0.009 | 0.8 | $\frac{1}{19310}$ | 17.26 | 3.50 | 2.2 | $15.8^h$ | 2 |
| Pluto | 39.52 | 0.247 | 15.7 | ? | ? | ? | ? | $6^d$(?) | 0 |

* Astronomical Unit, i.e., the mean distance from the Earth to the Sun, equal to 149.5 million km

The eccentricity, i.e., the ratio of the distance between the focus and the centre of the conic to the major semi-axis, of most planetary orbits is less than 0.1, reaching a noticeable magnitude only in Mercury and Pluto, the planets located at the extremities of the system.

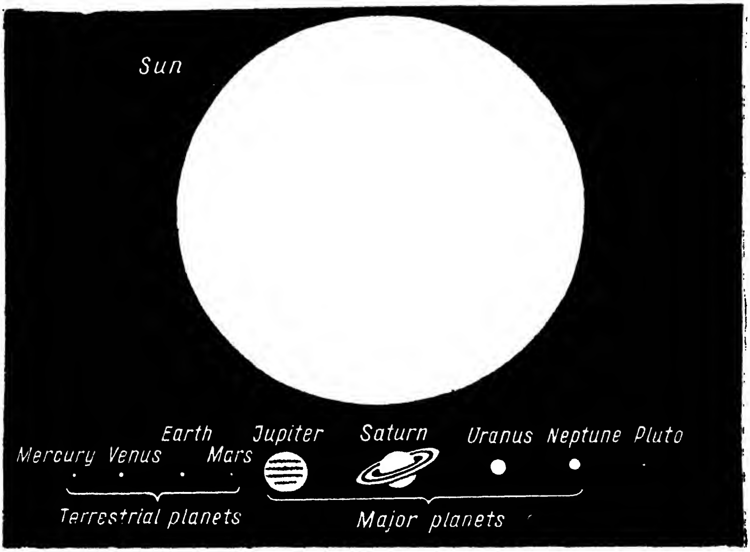



*Fig. 4.* Comparative dimensions of sun and planets

The table also shows the inclinations of the planetary orbits, in relation not, as customarily, to the ecliptic plane of the Earth's orbit, but to the main plane of the entire planetary system. This main plane characterizes the position of the central (equatorial) plane of the cloud of diffuse matter from which, as we shall see later, the planetary system originated. The inclination of the orbits is small for most of the planets, being the greatest, again, for the extreme planets, Mercury and Pluto.

As already stated, the planets are far smaller than the Sun both in dimension and mass (see Fig. 4 and Table 1).

The aggregate mass of all the planets is but $^1/_{745}$ of the Sun's mass. Thus 99.87 per cent of the mass of all the known bodies of the solar system is concentrated in the Sun. We say of all bodies, because the mass of each of the asteroids and comets is so insignificant that even in the aggregate their mass is much smaller than that of the Earth.

The difference between terrestrial and giant planets is manifested not only in scale and density, but also in the velocity of their axial rotation and in the number of satellites.

Even if we disregard Mercury and Venus, whose slow rotation is probably connected with their proximity to the Sun, we see that such enormous planets as Jupiter and Saturn rotate at twice the speed of the comparatively smaller Earth and Mars. Whereas the planets of the Earth group have either no satellites or only one or two, Jupiter has twelve, while Saturn, in addition to nine large satellites, has a number of minute ones, which, to the naked eye, form a solid ring.

The motion and structure of the planets are conditioned by their genesis. To obtain a correct conception of their genesis, we must analyze the movements and structure and, from a single point of view, explain the similarities and differences between the planets and also between the planets and other bodies of the solar system.

* * *

The distribution of the angular momentum among the separate bodies is of great importance in assessing the origin of matter forming the components of the solar system.

In mechanics, momentum is the mass of a body multiplied by its velocity ($mv$). An important characteristic of the rotation of a body around a certain primary is the angular momentum, i.e., the mass of a body multiplied by its velocity and by the radius of its orbit ($mvR$). If the orbit is not

exactly circular, a velocity component, perpendicular to the radius vector, is taken. In the case of a body rotating on its own axis, the velocity and distance from the axis vary at different points. Here we should mentally divide the body into small elementary volumes, calculate the angular momentum for each and then add up the sum.

The law of the conservation of angular momentum holds good for systems isolated from external influences and developing under the action of exclusively inner forces: the total angular momentum remains constant. It can only be redistributed among the separate components of the system. Therein lies the essential difference between the entire angular momentum of a system and its entire stock of mechanical (kinetic and potential) energy. The mechanical energy even of isolated systems can change. For instance, it can, as a result of friction, be transformed into thermal energy.

Throughout its existence, the planetary system has not been subjected to external forces which could have augmented its stock of angular momentum. Consequently, the planets acquired their angular momentum during their formation, deriving it from the matter from which they originated.

As already noted, the movements of the planets and the dependence of their physical properties on the distance from the Sun prove that they were not taken over by the Sun "ready-made," but were formed about the same time, in its vicinity, and from matter already revolving around it.

Let us now consider the angular momenta of the planets which are contained in their orbital movement around the Sun.

It is common knowledge that the greater the distance from the Sun, the slower the planet's movement along its orbit. But the decrease in velocity is in the radio of $1/\sqrt{R}$, i.e., slower than the increase in distance ($R$). As a result, angular momentum per unit of mass (specific angular momentum) increases in ratio to the square root of the orbital radius ($R$: $\sqrt{R} = \sqrt{R}$). For movement along an ellip-

the orbit with major semi-axis equal to $a$ and eccentricity equal to $e$, the specific angular momentum is in direct ratio to the value $\sqrt{a(1-e^2)}$.

Table 2 gives the full and specific angular momenta of planetary orbital motion compared to the Earth's.

*Table 2*

**Full and Specific Angular Momenta of Planets**

| Name of Planet | Full Angular Momentum | Specific Angular Momentum |
|---|---|---|
| Mercury | 0.03 | 0.61 |
| Venus | 0.69 | 0.85 |
| Earth | 1.0 | 1.00 |
| Mars | 0.13 | 1.23 |
| Jupiter | 725 | 2.28 |
| Saturn | 294 | 3.08 |
| Uranus | 64 | 4.38 |
| Neptune | 95 | 5.48 |
| Pluto (circa) | 1 | 6.09 |
| | 1181 | |

Since we do not know the rotational velocity of the internal layers of the Sun, we cannot, therefore, calculate its full angular momentum exactly. In terms of the units accepted by us, it is not more than 20.

Comparison of the angular momenta of the Sun and the planets shows that although the Sun possesses the "lion's share" of the aggregate mass, its axial rotation produces no more than two per cent of the aggregate angular momentum of the entire solar system, with the other 98-99 per cent concentrated in the orbital movement of the planets.

The difference between the specific angular momenta of the planets and the Sun is still greater. The mean angular momentum of the planets, calculated with consideration for their mass, equals 2.63. The Sun's mean specific angular momentum can be reckoned by dividing its full angular mo-

mentum by its mass in terms of the Farth's mass. It comprises at the maximum $\frac{20}{333000}=\frac{1}{16650}$, i.e., at least 45,000 times less than the mean specific angular momentum of the planets.

The distribution of angular momentum between the Sun and the planets claimed the attention of scientists in the 60's of the last century when the Laplacian hypothesis was subjected to critical analysis. It was the stumbling block to this hypothesis and to the bulk of the cosmogonic hypotheses which replaced it.

## 2. THE DEVELOPMENT OF PLANETARY COSMOGONY

Cosmogony originated as a science in the 18th century. The middle of the 18th century was an important landmark in the advance of natural science, when the old views on Nature's immutability were beginning to give way to the new conceptions of continuous evolution, continuous development. Mikhail Lomonosov, the brilliant Russian scientist, wrote then: "Thou shalt firmly bear in mind that corporeities thou seest on earth and the whole world were not ever thus at their conception as thou now findest, but great have been the changes wrought within."

Astronomy was one of the first sciences to shake the unsound and petrified world outlook. The concept of development entered into astronomy at the very end of the 18th century. Credit for this goes to Laplace who in 1796 pictured the formation of the Sun and planets from an immense gaseous nebula.

It was subsequently learned that forty years earlier, in 1755, the German philosopher Kant had put out a little booklet in which he boldly declared: "Give me matter, and I will show you how to make a world of it." In this work, Kant analyzed the problem of the evolution of the world and the laws governing the origin of all celestial bodies, and expounded a hypothesis on the formation of the solar system from diffuse matter.

Kant's book, which was published anonymously, drew no comments from the scientists of the day—it began to attract attention only in the 19th century. The hypotheses advanced by Kant and Laplace are of immense importance; they postulated the idea of the evolution of universal matter on the basis of inherent properties, without divine intervention.

* * *

In their endeavour to ascertain the origin and evolution of the Earth and other planets, both Kant and Laplace proceeded from the regularities in the structure of the solar system.

It was Newton that first drew attention to the laws of planetary motion. After discovering the fundamental laws of mechanics and the law of universal gravitation governing planetary movement around the Sun, Newton reached the conclusion that the planetary system was not a fortuitous agglomeration. But instead of seeing in this the outcome of the evolution of matter, resulting in the formation of the solar system, Newton, a devout believer, saw in it an indication of divine creation.

In his famous *Mathematical Principles of Natural Philosophy (Philosophiae Naturalis Principia Mathematica)* he wrote: "The six primary planets* are revolved about the sun in circles concentric with the sun, and with motions directed towards the same parts, and almost in the same plane. Ten moons are revolved about the Earth, Jupiter, and Saturn, in circles concentric with them, with the same direction of motion, and nearly in the planes of the orbits of those planets; but it is not to be conceived that mere mechanical causes could give birth to so many regular motions, since the comets range over all parts of the heavens

* In Newton's time Uranus, Neptune and Pluto were still unknown, and only 10 satellites, the Earth's one, Jupiter's four and Saturn's five, had been discovered.

in very eccentric orbits; for by that kind of motion they pass easily through the orbits of the planets, and with great rapidity; and in their aphelions,* where they move the slowest, and are detained the longest, they recede to the greatest distances from each other, and hence suffer the least disturbance from their mutual attractions. This most beautiful system of the Sun, planets, and comets, could only proceed from the counsel and dominion of an intelligent and powerful Being."

In 1745, Buffon, the French naturalist, suggested that the Earth and other planets had originated from splashes of solar matter torn off the Sun when struck by a huge comet.** Buffon substituted for the divine "act of creation" a natural phenomenon, and therein lies the progressive significance of his hypothesis. But in essence his explanation of the origin of the solar system was wrong. As Laplace indicated, the fragments should have followed elongated elliptical orbits and reverted to the Sun. Even if the reciprocal attraction of the fragments had changed their orbits, preventing their return to the Sun, they would have moved along elongated paths unlike the present circular orbits of the planets. Buffon's hypothesis did not take into account the regularities of planetary motion, although they had already attracted the attention of scientists. Hence, despite its progressive character it was not abreast of the times.

In 1796, Laplace, the renowned French astronomer and mathematician, published a popular book on astronomy, *Exposition of the World System*. In notes at the end of this book he set out a hypothesis of the origin of the solar system largely similar to Kant's hypothesis. The Laplacian hypothesis rapidly won recognition and enjoyed great popularity for 150 years. This was because it gave an exceed-

* *Aphelion*—the point of a planet's or comet's orbit farthest from the Sun.

** At that time comets were thought to be large heavenly bodies. Actually, their cores are very small, and the huge luminescent heads and tails are composed of exceedingly rarefied gases.

ingly simple and striking explanation of the characteristics of planetary orbital motion already mentioned.

According to Laplace, the planetary system originated from the hot rarefied atmosphere surrounding the primeval Sun and extending far beyond the confines of the present solar system. In his view, this nebulous, gaseous atmosphere around the Sun revolved like a solid body with the outer part moving faster than the interior. Gradually, it cooled and contracted. Due to contraction, it must have rotated faster in conformity with the law of conservation of angular momentum. Eventually, the equatorial centrifugal force equalled the force of attraction. The matter of the nebulous equatorial belt broke away and remained at the point where the break took place, while the rest of the gas continued to contract.

Once begun, this process continued and, as a result, a huge flat layer of gas, like Saturn's rings, remained in the nebula's equatorial plane. Gaps appeared in this enormous disc. They gradually widened, the gaseous substance condensing into isolated narrow rings. These rings were not quite homogeneous, with the result that their substance coagulated into hot, gaseous agglomerations, which, after cooling, became the planets. Planets formed in this way would move in circular orbits and all in one direction, that of the rotation of the original nebula, while all their orbits would lie in one plane, that of the equator of the primeval nebula.

Although he was both astronomer and mathematician, Laplace presented his hypothesis in a purely descriptive form. In doing so he proceeded from an analysis of the regularities of planetary motion and from the results of Herschel's observations of nebulae possessing varying degrees of condensation towards a bright central core, then held to be newly originating stars. Laplace postulated that they were akin to his primordial nebula.

The computations made by the French mathematician Roche in the middle of the last century showed that in spin-

ning faster and faster Laplace's nebula should have flattened under centrifugal force to assume finally the shape of a lentil bean. It was from the edge of this "lentil" that the matter should have split off.

If we imagine planetary matter as distributed throughout an enormous gaseous disc, its density would be so small that the contraction of the gas into denser rings would be incomprehensible. To get round this, Roche indicated a possible intermittent process, wherein it was not a disc but separate narrow rings that split off. On all drawings, the genesis of the solar system according to Laplace's hypothesis is depicted with Roche's corrections (see Fig. 5).

Laplace believed that, due to strong inner friction, the gaseous ring should revolve as a solid body, i.e., all the ring's particles moved with an identical angular velocity. This implied that the ring's outer rim moved faster than the inside edge (see Fig. 6, left), and therefore when the ring's substance contracted into a single gaseous agglomeration—the future planet—it would rotate on its axis in the same direction that it revolved around the Sun (the direct rotation). Cooling and shrinkage of the agglomeration must have been accompanied by accelerated rotation and in some cases with rings breaking away from the future planet to form satellites.

In 1796, when Laplace published his hypothesis, only satellites with a direct revolution were known. But in 1797, it was discovered that Uranus' satellites revolve in a plane nearly perpendicular to its orbit. In 1847, Neptune was found to have a satellite with a retrograde motion, and during the last half century both Jupiter and Saturn were found to possess satellites with retrograde motions. In 1877, Mars was found to have two satellites. Their motion is direct, but it was ascertained that the nearest Martian satellite, Phobos, revolves around its planet three times as fast as the latter rotates on its own axis. These facts contradicted Laplace's hypothesis.

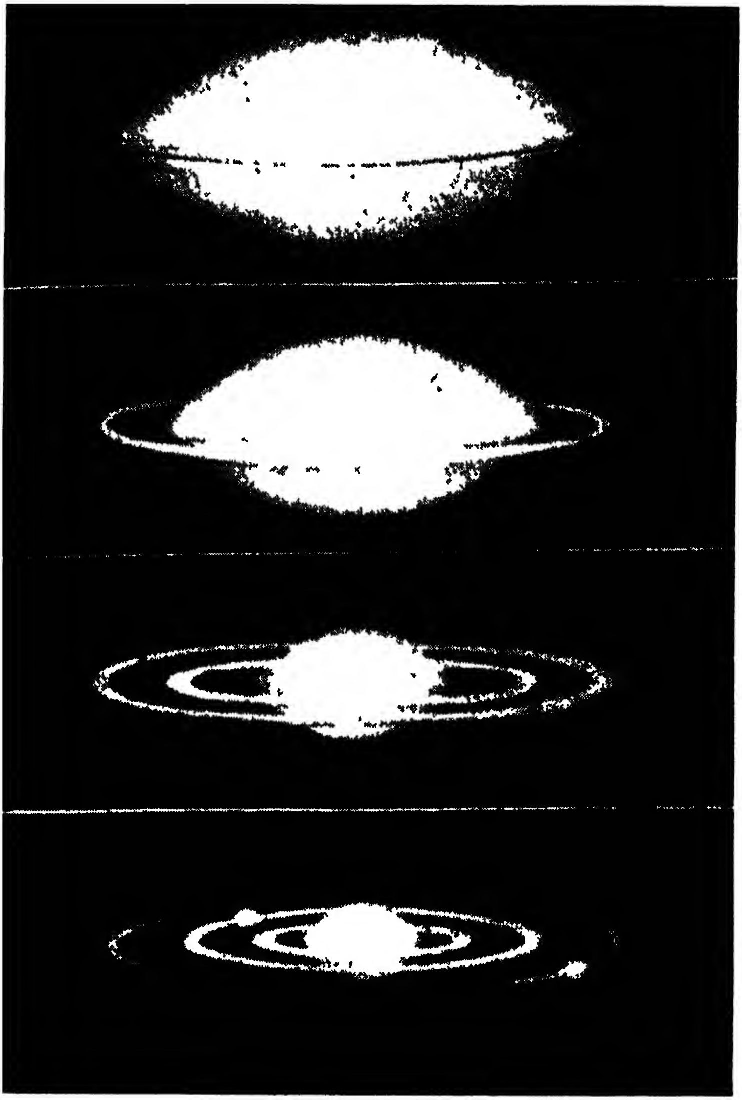


*Fig. 5.* Laplace's hypothesis of planetary formation

Some astronomers noted that the Laplacian rings, even if narrow, would have been so rarefied that the negligible inner friction could not have compelled them to revolve as solid bodies. Their revolution would have been similar to planetary movement round the Sun: the farther away from the Sun, the slower the rotation. Hence, the rotation of the agglomerations formed from the rings would have been retrograde (Fig. 6, right). Thus, not the retrograde motion of the satellites, but their direct motion and the direct rotation of the planets contradict Laplace's hypothesis.

*Fig. 6.* Origin of planetary rotation according to Laplace's hypothesis. Left: Origin of direct rotation. Right: Origin of retrograde rotation

The exceedingly artificial schemes put forward to solve this contradiction failed to satisfy anyone. As we shall see later, during the formation of the planets from diffuse matter, they must, as a rule, rotate directly, but to obtain this, the transformation of part of their mechanical energy into heat, which was inevitably the case, must be taken into account. Laplace was still in the dark as to the law of conservation of energy, while his followers for some reason or other disregarded this law in their investigations.

In Laplace's time, the kinetic theory of gases was still unknown, as was also the behaviour of gas molecules in different physical conditions. Subsequent calculations showed that rarefied gaseous rings could not have condensed into planets, but would have dissipated into space. But according to modern science, Laplace's gaseous disc, even if it

has a high degree of heat at the moment of its formation, should have rapidly cooled, and condensation, the formation of solid dust particles, should have begun within it. The evolution of this gas-dust matter differs essentially from Laplace's conjectures.

One of the main arguments disproving Laplace's hypothesis is based on the very slow rotation of the Sun. Proceeding from the rotating velocity of the primordial nebula, which had to be great enough to permit rings to break off, we can compute the rotating velocity of the Sun, as condensed from this nebula's core. Then, the velocity of the Sun's rotation should be hundreds of times greater than currently observed. Conversely, if we imagine the Sun extended to the dimensions of the entire planetary system, rotation would be so slow that detachment of the rings would be out of the question. Laplace's hypothesis proved powerless to explain the distribution of the angular momentum between the Sun and planets.

The Soviet astronomers V. A. Krat and V. G. Fesenkov pointed out a few years back that ejection of streams of atoms from the Sun's surface, negligible at present, might have been very intensive shortly after its formation and, if so, could have slackened its rotation. But today most astronomers believe the Sun's mass was from the very beginning near to what it is now, or, in other words, that the ejection of atoms was not particularly intensive in the past either.

The hypotheses of Kant and Laplace, abreast of the science of their day, were disproved by later knowledge. Attempts to patch them up proved of no avail, and in the 20th century astronomers turned to other hypotheses, neglecting even the merits of the Kantian and Laplacian theories, the idea of the planetary system deriving from a unitary, revolving diffuse nebula.

The numerous cosmogonic hypotheses of the 19th and 20th centuries were not based on all the then known facts about the bodies of the solar system, ignored the im-

portance of physical laws for cosmogony and, for this reason, were soon found wanting. Some of them were worthless, others had their merits, but were clogged with erroneous and even fantastic ideas.

Towards the end of the 19th century, the Belgian, Ligondès, advanced the meteoritic hypothesis of the origin of the solar system. Ligondès rightly indicated that in a swarm of particles there must be non-elastic collisions as well as cohesion. As a result, the particles settled into an extremely flattened rotating disc, from which the planets were formed.

The hypothesis of two American scientists, Moulton and Chamberlin, who also supposed the Earth and the planets to have originated from minute solid particles revolving around the Sun, appeared at roughly the same time. They postulated that these particles, which they called "planetesimals," had been brought into being by the cooling of a substance ejected from the Sun in enormous prominences.

Moulton and Chamberlin disregarded the non-elastic character of the particles' collisions and failed therefore to explain why the particles had agglomerated into planets. This was one of the main reasons why their hypothesis was soon rejected. But in point of fact, their error was that they had wrongly conceived the formative process of the swarm of particles; the ejection of matter from the Sun could not have given rise to particles with such an angular momentum as the planets now possess. At the same time the planetesimal hypothesis correctly depicted many features of the process of planetary formation.

Of the hypotheses that appeared in the first half of the 20th century, that of the British astronomer Jeans enjoyed wide popularity in the 20's and 30's. Jeans tried to get over the stumbling-block of the distribution of angular momentum between the Sun and planets by suggesting that the substance of which the planets are made had been torn out of the Sun by the attraction of a massive star speeding past in the vicinity (Fig. 7). The star, ostensi-

bly, had drawn the torn-off substance sufficiently far away from the Sun and compelled it to revolve around the Sun in the direction of its movement.

The stars are so far apart that an encounter between two of their number is an extremely rare phenomenon. Therefore Jeans' hypothesis maintained that the planetary system was an extraordinary formation in the universe. As Academician Schmidt puts it, "...What, in the astronomer's view, was the shortcoming of Jeans' hypothesis—the faint probability, i. e., the extreme rarity of the planetary formation process—became its chief merit in the eyes of the layman who did not want to break with religion. Jeans' hypothesis was the most acceptable compromise. The rarity of planetary formation in Jeans' scheme is, of course, still not idealism in itself—there are rare phenomena in Nature—but it opened the gates to idealism in cosmogony."

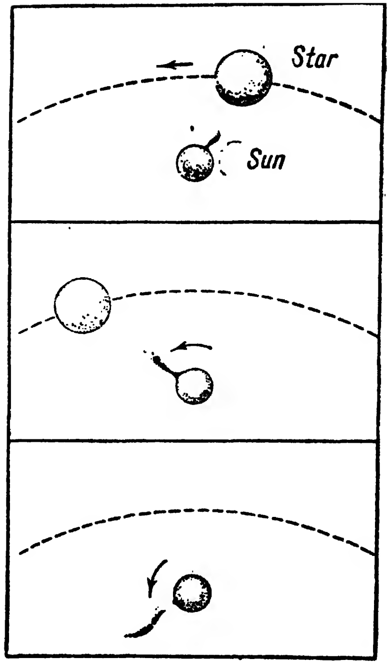



*Fig.* 7. Jean's hypothesis of planetary formation

However, some 15 or 20 years ago the scientific invalidity of this hypothesis was made clear. Russel, an American astronomer, pointed out in 1937 that Jean's hypothesis cannot provide an explanation for the vast dimensions of the solar system. In order to tear matter out of the Sun, the star's passage must have been very close, and in this case the fragment and the planets to which it gave birth

should circle in the Sun's immediate vicinity at a distance of only a few times its diameter. Actually, the planets are separated from the Sun by distances thousands of times its diameter. Thus, the distance between Jupiter and the Sun is 500 times the latter's diameter, between Neptune and the Sun 3,200 times the Sun's diameter. N. N. Pariisky proved by means of mathematical calculations that Jeans' hypothesis cannot explain the enormous distances between the Sun and planets.

In essence, this is again the question of the distribution of angular momentum throughout the solar system. But if in the case of Laplace's hypothesis the matter can be put thus: Why does the Sun revolve so slowly? Why is its angular momentum so slight?—for Jeans' hypothesis it would be: Whence the tremendous angular momenta of the planets?

Jeans never attempted to calculate the condensation into planets of the substance detached from the Sun. But when calculations were made it turned out that a flow of matter should have gushed out from comparatively deep layers of the Sun, where temperatures are much higher than at the surface. The temperature of the flow would have reached about one million degrees, and the flow could not have split into separate stable planetary agglomerations; it would have dispersed in space.

* * *

The feature of modern planetary cosmogony is that all theorists conjecture planetary formation as deriving from a cold, circum-solar gas-dust cloud. They differ in their views on the origin of the proto-planetary cloud and on the process itself of planetary formation.

Astronomers began to regard the planets as having arisen from diffuse matter in the 40's, shortly after Jeans' hypothesis was disproved. This turn in astronomical

minds was initiated by the hypotheses of the German physicist C. von Weitzsacker and Academician Otto Schmidt, which appeared almost simultaneously—1943-44.*

Weitzsacker believes that at one time the Sun was surrounded by a revolving gas-dust, disc-shaped cloud. Its mass was about a tenth of the Sun's present mass.

The planets formed in this cloud through gradual accretion of dispersed matter from surrounding space. To explain the regularities in the distances from the Sun to the planets, Weitzsacker presumed there had been regular annular systems of vast vortices. The smaller vortices arising in strictly definite places between the bigger vortices, produced condensations which subsequently developed into the planets of today.

Weitzsacker's hypothesis did not gain recognition, chiefly because of the artificial character of the surmise as to a regular system of vortices. Nevertheless, the idea of a gas-dust proto-planetary cloud acted as a spur to several Western scientists (Ter-Haar, Kuiper).

The late Academician Schmidt approached the problem by analyzing the principal regularities of the orbital motions of the planets. He inferred that the planets had formed from a swarm of bodies of varying sizes by gradual accretion. Later, he found a simple explanation for the origin of planetary rotation, and indicated an explanation for the regularity in planetary distances from the Sun. In 1949-50, when data on the chemical composition of the planets were drawn upon, it was found that the swarm of bodies had originated in the Sun's neighbourhood from the gas-dust cloud. To explain the distribution of angular momentum between the Sun and the planets, Otto Schmidt suggested that the planetary substance had been captured by the Sun. Believing at first that it was the swarm of bodies that had been captured, he afterwards adhered to

* Because of wartime circumstances the Soviet scientists first learnt of Weitzsacker's hypothesis from American journals in 1945.

the view that it was the gas-dust proto-planetary cloud. Otto Schmidt paid close attention to the geophysical consequences of the new notions of the Earth's formation process. One of the main conclusions is that at its origin the Earth was cold. Only later did it gradually warm up through the accumulation of heat emitted by radioactive elements in disintegration. The work of Academician Schmidt and his team of scientists will be described in greater detail elsewhere in this book.

In 1949 the American astronomer Kuiper, influenced by Weitzsacker's hypothesis, began to study the origin of the planetary system from the circum-solar gas-dust cloud, and is continuing this work today. At first Kuiper took from Weitzsacker also the idea of the importance of turbulence in the proto-planetary cloud. He, however, regarded planetary formation not as a gradual process of growth, but, on the contrary, as the gradual dispersion of the bulk of the substance from massive condensations—proto-planets. He believes that the evolution of the proto-planetary cloud began with the formation of such proto-planets, one for each planet. Upon contracting to form the present planets, they must have warmed up.

Kuiper maintains that the Sun owes its origin to the contraction of a nebula, and that the proto-planetary cloud came into being in this process from the same primordial nebula. He presumed at first that the proto-planets took shape after the Sun had become a radiating star. Later he revised this view and now claims that the proto-planets originated when the Sun was still in the process of formation and could not emit as yet radiation; hence the proto-planetary cloud must have been quite cold. After the Sun "flashed forth" as a star, its radiation made excess matter "evaporate" from the proto-planets. Though Kuiper does not detail the question of the Earth's chemical composition, he presumes proto-Earth to have lost not only volatile gases, but even part of its silicates.

Yet it is precisely the many specific features of the Earth's chemical composition that speak against the idea of its having originated from a massive gaseous proto-planet (see Chapter 5). Moreover, a critical analysis of the question of the proto-planetary cloud's evolution shows that it could not have broken up into Kuiper's massive proto-planets.

In recent years Kuiper has changed his views on the formation of the terrestrial group of planets. He now admits the importance of the accumulation of solid particles in this process. Somewhat earlier he abandoned his surmises as to the asteroids and the small planetary satellites having originated from gas condensations and came round to the view that they had formed via accumulation. Thus, Kuiper has come considerably closer to a conception of the formation process of planetary bodies elaborated, for example, by Schmidt in his cosmogonic theory.

In 1951, Academician Fesenkov, hitherto a supporter of the hypothesis of the separation of the planets from a fast spinning Sun due to centrifugal forces, began to conjecture planet formation as originating in the gas-dust cloud. In this he sided with Kuiper in believing that both the Sun and the cloud had originated at one and the same time and that the cloud had broken up into massive proto-planets, one for each planet.

The American physico-chemist H. C. Urey began to elaborate his cosmogonic theory in the same year. At variance with most students who base themselves primarily on astronomical data about the planetary system, Urey proceeds mainly from data on the chemical composition of planets and meteorites. He averred that the accumulation of cold solid particles had been chiefly responsible for the Earth's formation. He has, therefore, much in common with Schmidt. However, he believes that when the swarm of intermediate asteroid-size bodies was formed, their surfaces were heated. He needs this as he holds to earlier views maintaining that the dense core of the Earth con-

sists of iron. If that were so we would have to ascribe the difference in the mean densities of Mercury, Venus, the Earth, Mars and the Moon to difference in metallic iron content. Urey explains the difference by the heating up of the surface of the intermediate bodies, in the process of which part of the silicates evaporated. The difficulties he encounters in doing so force him to look for newer and newer causes and forms of this heating-up process.

Planetary formation via the accumulation of solid substances is conjectured also by the British scientists Edgeworth (1949), Hoyle (1955), and Gold (1956). It is a thesis that has gained wide currency in recent years. Winding up a survey of new data on the Earth's constitution, the well-known geo-physicist Prof. B. Gutenberg wrote in 1956: "An ever-increasing number of astro-physicists and geo-physicists think it likely that Earth was formed through the gradual accretion of cold matter, and many geologists express the view that the Earth was never in a fully molten state."

The cosmogonic hypothesis of the Swedish physicist Alfvén occupies a special place. He believes that at the time of planetary formation the Sun had a rather strong magnetic field and, hence, the entire process was swayed by electro-magnetic forces. The cosmic gas-cloud fell towards the Sun due to the latter's attraction and, by degrees, the atoms of the different gases were ionized as a result of collisions. As soon as they had become electrically charged, the Sun's magnetic field retarded their fall and impelled them to revolve round it, simultaneously imparting to them part of its angular momentum. In other words, the Sun's rotation slowed down. In this process the primordial cloud should have divided according to its chemical composition: the gases ionized easiest, notably, iron and silicon, stop first, i.e., farthest from the Sun; next in order, in somewhat closer proximity to the Sun, would be carbon dioxide, then helium, and finally, the nearest of all, hydrogen, which needs the greatest energy for ionization.

Actually, the picture is the reverse. The planets closer to the Sun contain much silicon and iron, while the farthermost abound in hydrogen. To explain the incongruity Alfvén had to surmise planetary formation from the small admixtures of other chemical elements present in both the inner and outer regions of the cloud after its division. Thus, the planets acquired their chemical composition notwithstanding the chemical division of the cloud which follows from the main point of Alfvén's hypothesis. His hypothesis has not gained recognition, since this and other of his conjectures—for instance, the Sun's having in the past a magnetic field thousands of times stronger than it does now—are artificial.

* * *

In our century the development of cosmogony in the capitalist countries is greatly hampered by the idealist outlook current there. Instead of a search for the real processes of planetary formation based on analysis of the maximum facts, more attention is given to an unjustified selection of the facts or to attempts to construct a cosmogonic theory based on preconceived notions of the dominance of one or another process.

Some Western astronomers even have recourse to religion. For example, the British Professor Smart in his book *The Origin of the Earth,* published by the Oxford University Press in 1951, writes "... to many of us, scientific and non-scientific alike, the belief in a Divine Creator is as necessary now as ever it was."

However, the pursuit of natural science impels scientists to take the materialist path. And so we find in the world of capitalism scientists who correctly, from a materialist angle, approach the study of the origin and evolution of cosmic bodies.

Cosmogony in the U.S.S.R. is based on the firm materialist tradition of Russian science, as reflected in the works of Lomonosov, Bredikhin, Mendeleyev and many others.

Soviet scientists are making a deeper study of the philosophy of dialectical materialism, applying it to better advantage in research.

In the 20's and 30's Soviet astronomers subjected the cosmogonic views of Western scientists of the 19th and 20th centuries to critical scrutiny.

Academician Fesenkov has occupied himself with cosmogonic investigation since the early 1920s. At first he conjectured planetary formation from vortices; in the late 30's he advanced the hypothesis of the separation of hot planetary condensations from the Sun as the result of the sudden acceleration of rotation caused by its fast contraction: since 1951, as already mentioned, his views have approached those of Kuiper. He has written many studies of planets and meteorites, interplanetary matter and zodiacal light.

The work done by Academician Schmidt, who showed that the Earth originated not from a condensation of hot solar gases, but via gradual accretion of a multitude of solid bodies, and that the Earth had been initially cold, made a big impression, adding to the interest in cosmogonic studies in the Soviet Union. In 1943, when Schmidt first began to work in this direction, he was a pioneer blazing a new trail. A few years later world planetary cosmogony revealed clearly that it was taking this road.

As a result of the work done by Schmidt and his colleagues, the foundations of a materialistic theory have been laid and its main points profoundly substantiated. Schmidt's theory is receiving further elaboration today.

## 3. ACADEMICIAN SCHMIDT'S THEORY OF PLANETARY FORMATION

The matter now comprising the Earth and the other planets has gone through a process of long and tortuous development. At various stages of this evolution the planetary system acquired its different properties. Hence, the proc-

ess of planetary formation can be visualized, and the evolution of planetary matter portrayed by analyzing the present features of the planets.

The movement of the planets around the Sun along circular orbits lying in almost the same plane points to planetary formation from diffuse matter scattered throughout the entire region of the present planetary system. Kant and Laplace presumed that this was a continuous dust or gaseous medium, from which the planets had accumulated. But, as Schmidt noted, the proto-planetary state of matter must have been a swarm comprised of a multitude of bodies, flying along different orbits and participating at the same time in the general rotation of the swarm around the Sun.

By analyzing the data on the composition of the planets we can probe still further into past aeons and elucidate the state of planetary matter even before the swarm stage. It has been found that in the process of planetary formation vaporization and condensation played an essential role. These processes cannot take place without solid and gaseous substances. Hence, the matter which gave rise to the planets was originally a gas-dust cloud.

Schmidt and other Soviet scientists (Gurevich, Lebedinsky, Levin, Safronov and Khilmi) have elucidated the principal features of the proto-planetary cloud's evolution and the planet-formation process. The entire process can be conventionally divided into two stages: first, the formation in the cloud of a swarm of relatively large bodies intermediary between the primordial dust particles and the present planets; and second, the accumulation of the intermediate bodies into planets.

The main motive factors of the evolution were: firstly, the action of the force of gravitation; secondly, the transformation of mechanical energy into heat and, thirdly, the action of physico-chemical forces, this last being of primary importance in the first stage of the cloud's evolution.

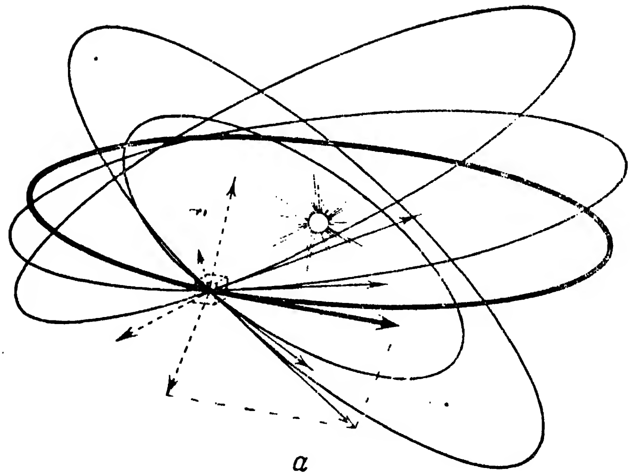
This stage began with the precipitation of the dust-specks to the central (equatorial) plane of the flattened cloud.*

The motion of the particles in the cloud can be divided into a general movement around the Sun and the chaotic movement of separate particles. The greater the mean velocity of the chaotic movement of the particles, the thicker the space they occupy. Fig. 8 furnishes an explanation for a case when particles freely follow locked orbits around the Sun. This is also true when a huge multitude of particles frequently collide and change their path, viz., switch from one orbit to another. Although in the interval between two consecutive collisions each particle flies along a very small distance of its orbit, the character of the relation between the velocities of chaotic movement and the thickness of the entire conglomeration of particles remains the same as it would be were there no collisions.

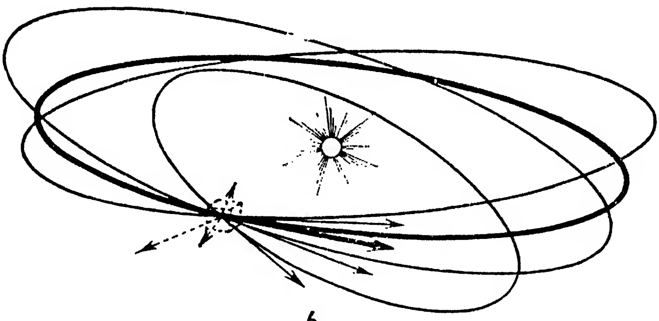
Due to their greater mass, the dust particles in the gas-dust cloud must have had far smaller chaotic velocities than the lighter gas molecules. Therefore the dust particles retreated to the central plane of the cloud, forming an oblate revolving disc (Fig. 9).

When the particles collected into this flat disc the distance between them diminished, while their mutual attraction increased. Then, when the disc had become sufficiently compact, numerous agglomerations began to form on the inside, capable of resisting the Sun's tidal force which sought to destroy the agglomerations. This destructive power is caused by the Sun attracting more strongly the part of the agglomeration nearer to it, thus seeking to stretch and tear it. This, however, is countered by the mutual attraction of the agglomeration's particles.

* Since the proto-planetary cloud rotated, it had a flattened form. Its central (equatorial) place is the main plane referred to on page 10 and in Table 1.



*a*



*b*

*Fig. 8.* Flattening of the space taken up by the particles as their chaotic movement decreases
a) high chaotic velocities
b) small chaotic velocities.
Thin arrows show the velocity of separate particles, thick arrows the velocity of the general circular movement, and the broken arrow the component of the velocities of the particles

The agglomerations revolved around the Sun in the direction of the cloud's rotation. At their origin they were swarms of isolated particles, localized condensations, in the cloud surrounding the Sun. Collisions of dust particles

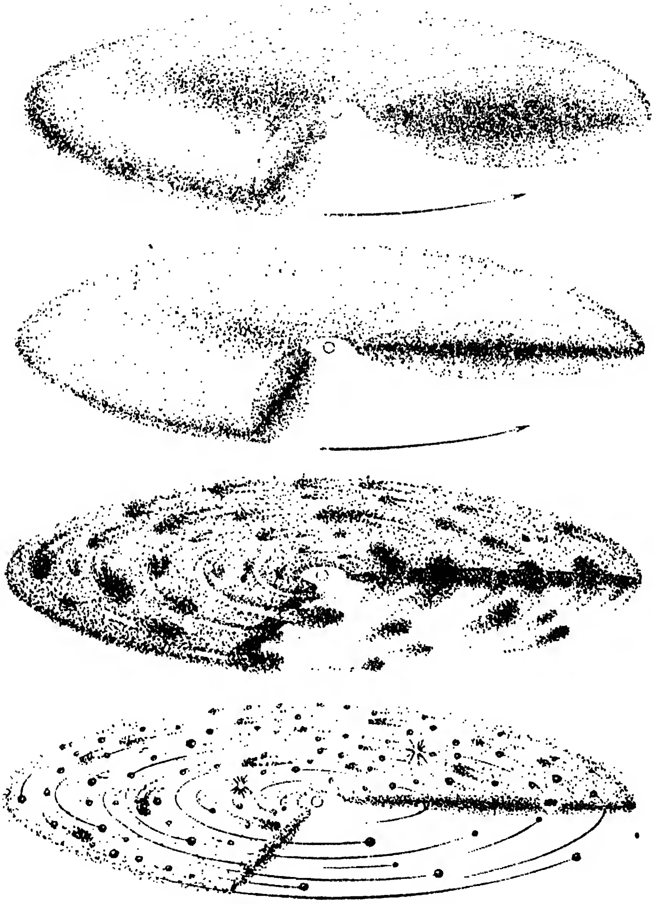


*Fig. 9.* First stage of evolution. The dust component of the proto planetary cloud is flattening and a multitude of asteroid bodies form from the dust disc

took place inside each swarm, also accompanied by transformation of mechanical energy into heat.

Collisions of gas atoms are elastic (if not in a heated state), i.e., the atoms rebound from each other with their

former velocities. Collisions of molecules are almost elastic, for only a very small part of their kinetic energy is emitted in the form of infra-red rays. But even this energy can be replenished if the gas is pierced by the Sun's rays. In absorbing radiation, the gas will partly re-emit it and partly transform it into the kinetic energy of its molecules.

Collisions between solid particles are non-elastic, with their relative velocities decreasing. In the collision the particles warm up, and a considerable portion of the kinetic energy of the dust particle is transformed into heat, which is then radiated into space and lost to the system.

Thus the collisions between the particles in the dust agglomeration were accompanied by a decrease in their relative velocities which led to the shrinkage of the agglomerations and their transformation into solid bodies, with diameters ranging from tens to hundreds of miles, that is into bodies the size of present-day asteroids.

It is quite possible that in some parts of the clouds the dust specks stuck to each other upon colliding. If, in this case, the flattening process was moderate, this gumming-together could have resulted in the formation of large bodies, even before the formation of dust agglomerations started. If, on the contrary, it was rapid, then the gumming-together would have been barely discernible, and the diminishing distances between the particles and the increase in their mutual attraction would have been the main factor.

At any rate, a huge number of relatively large bodies, intermediate between the primordial particles and the planets of today, formed in the dust disc. Collisions between these bodies entailed their complete or partial break-up, but the fragments, together with the primordial particles which had not yet been collected, formed new agglomerations, condensing, in turn, into new bodies. In the motion around the Sun, these bodies collected the sur-

rounding dispersed matter and thus rapidly increased in size. Bodies that escaped destruction in collisions, attained greater proportions, while those partially destroyed or of later origin lagged in growth. As a result, a multitude of bodies of different size and mass, growing through the accumulation of small particles, came into being in the cloud. The second phase of evolution, formation of planets from such a swarm of asteroidal bodies, began.

Some asteroidal bodies, formed in the first stage of the cloud's evolution were the "embryos" of the planets. These were larger bodies and, moreover, their motion was such that in the second stage of evolution, too, they grew faster than the rest, escaping destruction in collisions. In time, they became the present planets.

The asteroidal bodies came into being inside the dust disc and, at the outset, travelled along circular orbits lying in the plane of the disc. But, as they grew in mass, their gravitational pull on each other as well as on the dispersed matter—now already comprised of the residue of the primordial particles and the fragments of the splintered bodies—also increased. The chaotic movement of the asteroidal bodies and these particles gained in intensity; the swarm formed by them began to thicken. The interaction of the asteroidal bodies resulted in the appearance of increasing numbers of elongated and strongly inclined orbits among their originally almost circular orbits tilted but slightly to the disc's plane (Fig. 10). In this process the orbits of smaller bodies changed more, while those of bigger, less. Some of the particles and bodies, having acquired extremely elongated orbits, came so close to the Sun's flaming surface that they evaporated and joined the Sun's atmosphere in the forms of clouds of vapour. They participated in the general rotation around the Sun and, linking up with it, must have helped it revolve in the same direction, provided there was enough of them.

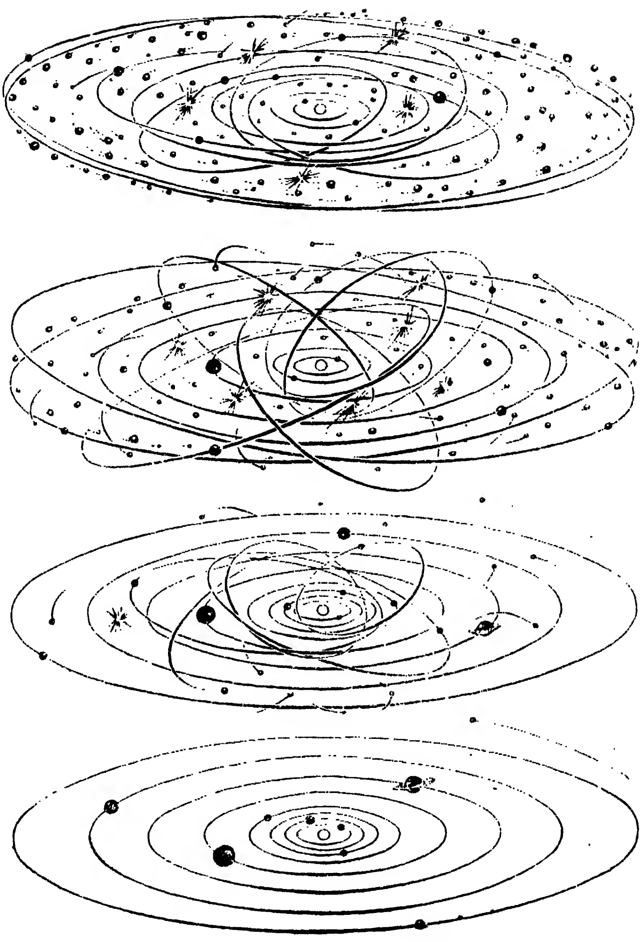


*Fig. 10.* Second stage of evolution. The flat system of asteroid bodies thickens and planets formed by gradual accretion of asteroidal bodies and their fragments

With a multitude of bodies agglomerating in the process of planetary formation, their specific movements must have averaged. And with a prevailing direction of movement, i.e., the general rotation of the swarm, the result would be planetary movement around the Sun in one and the same direction. The movements of the separate bodies along orbits elongated in different directions averaged to produce an almost circular orbit for the planet, while movements along orbits tilted at different angles to the swarm's central plane averaged to produce a movement into a plane, close to the central plane (Fig. 10).

At the outset, the asteroidal bodies grew through the particles directly colliding with their surface. But the attraction of the bigger "embryos" began to create local condensations of dispersed matter in their vicinity. The non-elastic collisions of particles in the condensed zone decreased their velocity, which often proved too weak for them to overcome the "embryo's" attraction and fly away. In this manner, the bigger "embryos" captured particles, i.e., turned them into their satellites. Later, the bulk of these particles fell on to the "embryos," so that their capture became one of the ways in which the "embryo," at a certain stage of its development, grew. In the case of massive "embryos" (for instance, the giant planets), growth through accretion probably even predominated over growth by the direct fall-out of particles.

At this stage of its growth, the future planet was surrounded by a swarm of particles. This, however, was not a dispersed swarm, akin to the condensations in the primordial dust disc, but a dense one, with a massive "embryo" inside. This swarm existed until the density of the dispersed matter sufficed for the capture of new particles to compensate for the gradual fall-out of the swarm's particles on to the "embryo's" surface. According as the growing "embryo" accumulated the surrounding matter, according as the disturbing action of its gravitation increased the thickness of the dust disc, the density of the

matter decreased, and the swarm of particles around a planet vanished, merging with the planet itself. Planetary growth through accretion ceased, there remained only growth via the direct fall-out of matter. In our times this process has almost ceased.

The hypotheses that the planets originated from a solid substance were usually known as meteoritic hypotheses, irrespective of whether they actually implied meteorites or minor dust particles, or both together. Hence, Academician Schmidt's theory is sometimes called the meteoritic theory. But this does not mean that the primordial particles of the solar cloud were of the same structure and size as the meteorites which fall out on the Earth now.

Meteorites are splinters of asteroids, that is, of the intermediate bodies existing to this day by virtue of being in the big gap between the orbits of Mars and Jupiter. Hence, if instead of the primordial particles we take the substance comprising the overwhelming part of the Earth's mass, we can say without hesitation that it is meteorite substance. The intermediate body which grew and became the Earth's "embryo" originated together with a multitude of other similar bodies, which disintegrated and again accumulated from fragments and primordial particles. The number of primordial particles that did not experience agglomeration and disintegration rapidly decreased, and soon the Earth's "embryo" was surrounded not so much by primordial particles as by bodies and fragments formed from them. Our planet's growth to its present dimensions was due chiefly not to the primordial particles but to these bodies and fragments, i.e., to bodies of a type akin to present-day meteorites.

At the beginning of the second phase of evolution there was in the vicinity of the Sun a whole swarm of asteroid-size bodies, each of which, given favourable conditions, could have become the "embryo" of a future planet.

Academician Schmidt analyzed relative distances of the orbits around the Sun of bodies that outstripped other

bodies in the process of growth and thus became planets.

The future planet attracted particles possessing either a slightly less or more specific angular momentum than the "embryo" itself. When most of the particles so attracted had a less specific angular momentum, the specific angular momentum of the "embryo" decreased, manifesting itself in reduction of orbital radius; the orbital radius grew gradually if the reverse was the case.

In the case of two "embryos" moving along comparatively close orbits, these orbits should have gradually diverged. The body nearer the Sun grew primarily at the expense of particles with still smaller orbits, whereas particles with greater orbits were intercepted and captured by the "embryo" farther away from the Sun. Conversely, the "embryo" farther away gained a lesser number of particles with smaller orbits and smaller specific angular momenta. Finally, the first "embryo's" orbit shifted towards the Sun, that of the second, away from the Sun. The tendency towards change in orbital radii would have ceased, had all the "embryos" shifted in their motion to the centre of their "feed zones." But owing to varying speeds in the growth of the neighbouring planets, this ultimate phase could not have been attained.

As Academician Schmidt shows, given a smooth distribution of matter in the proto-planetary cloud, the specific angular momentum would have increased to the same value if we compared one planet with the next farther away from the Sun. A planet's specific angular momentum is proportional to the square root of its orbital radius. Hence, the square roots of the planetary orbital radii would increase approximately in arithmetical progression:

$$\sqrt{R_n}=a+b\times n.$$

The division into terrestrial and giant planets reflects the difference in the properties of the inner and outer zones of the proto-planetary cloud. Therefore, the regu-

larity in planetary distances from the Sun must be regarded separately for near and remote planets.

Table 3 shows how true the above-mentioned formula is for the remote planets.

*Table 3*

| | Jupiter | Saturn | Uranus | Neptune | Pluto |
|---|---|---|---|---|---|
| $\sqrt{R}$ calculated. | 2.28 | 3.28 | 4.28 | 5.28 | 6.28 |
| $\sqrt{R}$ actual . . | 2.28 | 3.09 | 4.38 | 5.48 | 6.29 |

The results for the four terrestrial planets are given in Table 4.

*Table 4*

| | Mercury | Venus | Earth | Mars |
|---|---|---|---|---|
| $\sqrt{R}$ calculated. | 0.62 | 0.82 | 1.02 | 1.22 |
| $\sqrt{R}$ actual . . | 0.62 | 0.85 | 1.00 | 1.23 |

In these Tables, $\sqrt{R}$ calculated increases by 1 from planet to planet for the remote planets and by 0.20 for the terrestrial planets. But the regularity as such in the increase of planetary distance in both groups is close to the arithmetical progression for $\sqrt{R}$.

Explaining rotation of the planets on their axes had always been a knotty point for planetary cosmogony. Academician Schmidt found that the transformation of mechanical energy of the cloud's particles into heat was of great importance in the genesis of planetary rotation.

Two laws play an important part in planet formation—the law of conservation of angular momentum and the law of conservation of energy. The orbital angular momentum

of the bodies and particles from which a planet was formed must have passed wholly into its orbital angular momentum and rotation.

In contrast, not all the mechanical energy of the bodies and particles became that of the planet since in the collisions a certain portion was transformed into heat and radiated into space. This diminution of the stock of mechanical energy, disregarded in earlier investigations of the origin of planetary rotation, plays a very essential role. By means of mathematical analysis, Academician Schmidt showed that if a large enough fraction of the original stock of the mechanical energy of the bodies and particles were transformed into heat, the planet would acquire a direct rotation.

The equator of some of the planets, especially Uranus, is heavily inclined to the orbital plane. At the same time, the motion of the satellites of Mars, Jupiter, Saturn and Uranus, or at least of the main satellites, is not in the orbital plane, but in that of the planet's equator. This shows that the satellites originated together with the planets in a single process at a stage when the enlarged "embryos" had surrounded themselves with swarms of captured particles.

In these swarms the process of planet formation repeated itself, though on a smaller scale. As a result of non-elastic collisions of the particles, the swarms were transformed into flat rotating discs, which then formed the satellites. These satellites have a direct motion in the plane of the planet's equator, and their paths, like the planetary orbits, are nearly circular. Furthermore, the distances between the planet and its main satellites increase in the case of Jupiter, Saturn and Uranus with a certain regularity, almost similar to the increase in the distance between the Sun and the planets.

We have already mentioned the Sun's tidal force which prevented the formation of condensations until the dust specks assembled into a flattened disc with an increased

density of matter. A similar tidal force was exerted by the planets on the satellites originating around them. The tidal force grows with greater rapidity the nearer the satellites are to the central body; consequently, separate swarms of particles cannot exist in the immediate vicinity of the central body and, therefore, cannot originate there.

The denser the swarm, the greater the mutual gravitational attraction between its particles and the more it can approach the central body without disintegrating. A swarm of a density equal to that of the central body would be disrupted by tidal forces, if it approached to within two and a half times its radius. This distance is known as the Roche limit.

The Roche limit holds good for swarms and loose bodies, the particles of which are not linked by molecular force but are held together only by gravitational force. Solid bodies can safely enter the Roche limit, provided their dimensions do not exceed a few hundred miles. But at the same time rarefied swarms may be disrupted under tidal force at distances much greater than the Roche limit.

The formation of Saturn's rings, located within the Roche limit, is undoubtedly linked with Saturn's tidal force. Probably part of the flattened swarm surrounding Saturn penetrated within the Roche limit. Consequently, the matter in this part of the swarm could not agglomerate into a single body to become a satellite, but remained in the form of a flat ring, composed of a multitude of separate particles. But it is also probable that there is another reason, that perhaps several thousands of millions of years ago, a newly formed and still crumbly satellite was drawn within the Roche limit due to Saturn's continually increasing mass*; here it disintegrated and formed the ring.

* * *

* As the mass of the central body gradually increases, the orbital radius of the satellite moving around it decreases, and vice versa.

Academician Schmidt's theory follows the main trend of materialist cosmogony, the trend of Kant and Laplace, who envisaged the formation of the solar system from an extended cloud of diffuse matter. But even with regard to the motion of the bodies in the solar system (let alone the problem of their composition and inner structure, which Kant and Laplace did not examine at all), Schmidt's theory differs in principle in that it takes into account the process of the transformation of mechanical energy into heat, a process which, as we have already said, conditions the direction of the evolution of the primordial cloud.

It is interesting that Kant correctly outlined the evolution of the revolving dust cloud. But he could not substantiate his outline, which is quite understandable if one recalls the level of science at the middle of the 18th century. In the 19th and 20th centuries repeated attempts were made to substantiate it, but all failed, due to a mechanistic approach to investigation and disregard for the transition of mechanical energy into other forms. Incidentally, in the 70's of the last century, Frederick Engels wrote of the decisive role of this process:

"... The life process of a solar system presents itself as an interplay of attraction and repulsion, in which attraction gradually more and more gets the upper hand owing to repulsion being radiated into space in the form of heat and thus more and more becoming lost to the system."*

In Schmidt's theory, the transformation of mechanical energy into heat is accorded due attention, hence its success in explaining the primordial cloud's evolution and its transformation into a small number of large bodies, in explaining the basic laws of planetary motion.

F. Engels, *Dialectics of Nature*, English ed., 1946, pp. 40-41

## 4. THE ORIGIN OF THE PROTO-PLANETARY CLOUD

The problem of the origin of the proto-planetary cloud is incomparably more difficult than that of its further evolution. The appearance of the cloud is a process related to a still more remote past than that of planetary formation. The cloud's conversion into a system of planets, asteroids, meteorites, comets and meteoric particles has to some extent effaced the traces of its own genesis. Because of this, an analysis of the structure of the solar system and the composition of its elements, which resulted in establishing the planets' origin from the gas-dust cloud that had once surrounded the Sun, has so far yielded but meagre information as to the origin of this matter.

The problem of the cloud's origin is closely bound up with the still unsolved problems of the origin of the Sun and the other stars. Currently, Ambartsumyan, Gurevich, Lebedinsky, Oort, Struve, Fesenkov, and other Soviet and foreign astronomers are elaborating stellar cosmogony, but at the present moment stellar cosmogony lacks a common point of view with regard to the original state of the matter of which stars are made, or to the process of their making. Due to this circumstance, astronomers are still divided as to the origin of the proto-planetary cloud.

In the Galaxy, the stellar system including our Sun, interstellar space is not a void; it is filled with diffuse matter, more or less rarefied, in a gaseous and dust state. Gas atoms are emitted from the surface of the stars, and, some distance away from them in the frigid zones of interstellar space, they partially fuse into molecules, some of which condense into dust particles.

On the one hand, in the Galaxy a process of dissipation of matter by the stars and other heavenly bodies is under way, on the other, heavenly bodies are being formed from diffuse matter. Astronomical achievements confront cosmogony with the necessity of examining the complex and multifold interaction of large bodies and diffuse matter.

*Fig. 11.* Dark (dust) and light (dust and gas) nebulae against the background of the Galaxy

Today there are two principal hypotheses concerning the origin of the proto-planetary cloud. One is that the Sun "captured" matter from surrounding space, the other, that the Sun and the cloud originated at one and the same time, that the cloud separated from the same gas-dust agglomeration from which the Sun itself originated.

At the very beginning of his research Schmidt suggested that the Sun had captured the matter that later made up the

planets. This hypothesis makes possible the explanation for the peculiar distribution of the mass and angular momentum between Sun and planets, something which none of the earlier cosmogonic hypotheses had succeeded in doing. In the event of a capture, the angular momentum of the cloud, and hence of the planets, is not directly connected with the Sun's momentum. It is derived from the angular momentum pertaining to the rotation of the stars and interstellar gas-dust clouds around the centre of the Galaxy, i.e., from the total store of the angular momentum of the entire Galaxy.

In their motion in the Galaxy, the stars, together with our Sun, pass through huge clouds of interstellar gas and dust. Academician Schmidt has shown that, in favourable conditions, they may capture a portion of the substance of these clouds. For this it is necessary that during a star's encounter with the cloud, the attraction of any other star in the vicinity should strongly retard their relative movement. Part of the cloud's substance may begin to revolve around the first star. Other Soviet astronomers have shown that the capture may be caused not only by force of attraction, but also by the diminishing speed during collisions of dust particles in the vicinity of the Sun (Agekyan), under the action of radiation pressure (Radzievsky) and other causes.

When beginning to elaborate his theory, Schmidt suggested that the capture could take place when the Sun, in its moving in the Galaxy and its participating in its rotation, accidentally encountered a gas-dust nebula. But, as calculations showed, in these conditions, which are similar to those in the present vicinity of the Sun, the chances of capture are slight because the Sun's velocity is, as a rule, extremely great in relation to interstellar clouds, averaging approximately 12 miles per second.

Soviet astronomers have established that, as a rule, stars originate not singly, but in clusters. According to one hypothesis, they are formed from interstellar gas-dust clouds. The newly formed stars in such a cluster would have com-

paratively low velocities both relative to each other and also to the remnants of the gas-dust cloud from which they derived. If the Sun originated in this way, then, in its early stages, the chance of capturing a cloud of gas and dust particles was millions of times greater than now.

Schmidt noted this in 1953. Although his studies led him to think in terms of gravitational capture, in the last years of his life he held that capture resulting from non-elastic collisions of particles in the neighbourhood of the Sun was the more likely and effective way.

In the opinion of other astronomers, for instance Kuiper and Fesenkov, the primordial cloud came into being simultaneously with the Sun. Thus, Academician Fesenkov believes the planets to have been formed from diffuse matter detached from the Sun in the process of its origin from an interstellar gas-dust condensation. He writes, "Before becoming a star, i. e., continuing to contract intensively, the Sun must have lost a considerable quantity of matter roughly in the equatorial plane, which due to the excessive speed of rotation could not collect into one body."* Since the process of the Sun's formation has so far been insufficiently studied, this hypothesis cannot be formulated in greater detail.

The Sun's equator does not coincide now with the central plane of the solar system, but is inclined towards it at 6°. If the initial cloud was captured by the Sun, then the central plane of this cloud is not bound up with the direction of the Sun's previous rotation, and its present rotation is the product of the sum of its previous rotation and the rotation acquired from the bodies and particles that fell on to it. In this case, the Sun's present equator should not necessarily coincide with the cloud's central plane; the proximity of the equator to the central plane shows that the role of the previous rotation is small at

* V. G. Fesenkov, *Origin and Evolution of Heavenly Bodies in the Light of Modern Data*, U.S.S.R. Academy of Sciences Publishing House, 1953, p. 55.

present, while that of the fall-out is great. If one accepts the simultaneous formation of the Sun and the initial cloud, then the inclination of the Sun's equator to the cloud's central plane necessitates a special explanation.

Irrespective of hypotheses as to the origin of the circum-solar gas-dust cloud, an analysis of its further evolution, an analysis of planetary formation, provides an explanation of the structure of the solar system and furnishes much of value for a correct conception of the Earth's structure and development. Furthermore, this analysis is of help in studying the origin of the Sun and the cloud itself.

The long existence of the planetary system around the Sun notably restricts hypotheses on the Sun's evolution throughout this period. Thus, as the author of this book showed in 1952, it refutes the hypothesis that the Sun appeared in the form of a very bright star with a mass five to ten times greater than now, and that during the process of its formation the planetary system originated.

## 5. THE COMPOSITION OF THE PLANETS

Similarities in the chemical composition of the Sun's upper layers and of the Earth have aways been adduced to confirm the view of the separation of planetary matter from the Sun. But in recent years data have been obtained on the quantitative chemical composition of many stars and nebulae. It has been found that stars, nebulae and interstellar matter alike have a similar chemical composition, with the comparative proportion of atoms of chemical elements in them being approximately equal. This is one of the manifestations of the material unity of the universe. Hence, the proto-planetary cloud could possess the same chemical composition both if captured from without and if separated from the Sun.

The most abundant chemical element in the universe is hydrogen, H (90% of the total number of atoms), with

the inert gas helium, He (9%), which does not enter into chemical compounds, second, and oxygen, O, nitrogen, N, and carbon, C, respectively third, fourth and fifth (aggregating roughly 0.3%). Silicon and the metals are infinitely scarcer. Where physical conditions permit association of atoms into molecules, hydrogen molecules, $H_2$, are formed; hydrogen compounds with other atoms existing in great number, i.e., oxygen, nitrogen, carbon, come into being to form molecules of water, $H_2O$, ammonia, $NH_3$, and methane, $CH_4$, and also molecules of carbon dioxide,

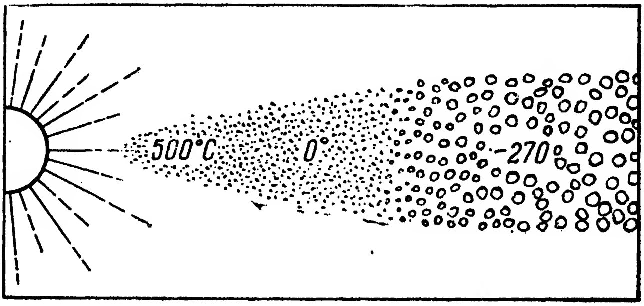



*Fig. 12.* Variation in particle dimension and composition in the inner and outer zones of the dust disc. This figure and also Fig. 13 conventionally show the different abundancy of dust at various distances from the Sun by the different thickness of the dust disc

$CO_2$. In this way many volatile substances are formed, existing in a solid state only at very low temperatures. Because of the small quantity of atoms of silicon and the metals, very few molecules of rocky substances* are formed.

Study of the physical and chemical processes that went on during the conversion of the initial cloud surrounding the Sun into separate planets makes it possible to explain the differences in planetary constitution and composi-

* Rocky substances chiefly consist of silicon and metal oxides ($SiO_2$, $FeO$, $Fe_2O_3$, $MgO$, $Al_2O_3$ etc.).

tion. The division into terrestrial and giant planets can be explained as follows. When at the first stage of evolution, the dust particles collected into an oblate disc, it became extremely opaque. The Sun's rays no longer penetrated into the parts of this disc farther away from the Sun, with the result that the temperature of the particles dropped to —270°C (3°above absolute zero), but the part nearer the Sun was heated by its rays.

Hence in the vicinity of the Sun there could exist only particles of refractory rock and metal substances. At the

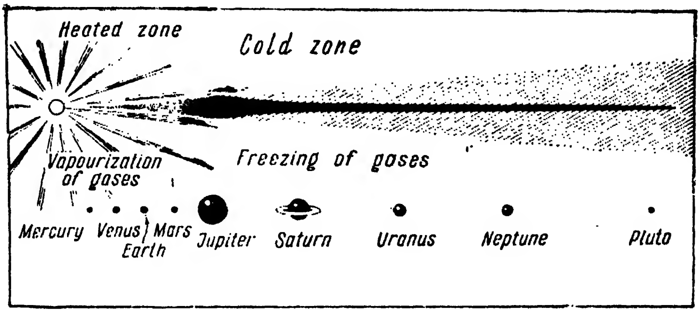



*Fig. 13.* Temperature distribution in the cloud, and planetary division into two groups

same time, far away from the Sun, in the frigid outer zone of the disc, the particles grew by accretion and freezing of the gases in the cloud surrounding the Sun (Fig. 12). These were hydrogen, methane, ammonia, vapour, carbon dioxide and other related molecules.

Differences in the chemical composition of the dust-disc particles became, during the transition to the second stage of evolution, differences in the chemical composition of the intermediate bodies and their fragments. With the formation of the swarm of asteroidal bodies tending to increase the transparency of the space they occupied, the border-line of the heated zone, in which there could only be rock substances, had to move somewhat further away

from the Sun. When particles and bodies composed of volatile substances penetrated into the swarm's inner zone, they rapidly evaporated, only their small rocky admixtures remaining. These zonal differences during condensation and evaporation resulted finally in the present division of planets into two groups.

In the vicinity of the Sun, the comparatively small terrestrial planets took shape from rocky substances, while at a great distance formation of the remote planets, composed of lighter substances, took place (Fig. 13). Spectrographical observations show that the atmospheres of the distant planets really contain much methane and ammonia. Without doubt Pluto's small dimensions are due to its being on the extreme outer fringe of the planetary system, but in composition it should be placed in the group of giant planets.

We see that the difference in composition and mass of the two groups of planets is due to the chemical properties of the elements and their compounds, their ability to condense into solid particles at certain temperatures.

It is these same properties that explain the peculiarities of the Earth's chemical composition, which previously were a riddle. For example, the Earth contains 10,000 times more oxygen than nitrogen (the Earth as a whole and not only its atmosphere). At the same time, the Sun and the universe in general have but three to five times more oxygen than nitrogen. The explanation is that, chemically, oxygen is highly active, while nitrogen is passive. Oxides, that is, oxygen compounds, are the main component of the rocky solid particles from which the Earth was formed, while compounds of chemically passive nitrogen are found in them in only a negligible quantity.*

---

* Though rocks contain only very small quantities of nitrogen, while air is almost 80 per cent of nitrogen, nonetheless, most of the Earth's nitrogen is concentrated in its interior. The reason for this is that the atmosphere comprises but a millionth of the Earth's entire mass.

Practically all the nitrogen remained in the circum-solar cloud.

The Earth has a still greater dearth of the inert gases, neon, krypton and xenon,* which, in general, do not compound chemically.

The Earth has thousands of millions of times less neon than the stars and the nebulae, hundreds of millions of times less krypton, and hundreds of thousands of times less xenon.

Earlier cosmogonic hypotheses, which inferred planetary formation from splashes of hot solar gases, explained the division of the planets into two groups as follows. Hydrogen and helium comprise the greater part of solar matter, and originally large quantities of these light gases entered into the composition of all the planets along with heavier chemical elements. But the massive giant planets, due to their great surface gravitation, were able to retain the atoms and molecules of these gases, while the small terrestrial planets, with their much lesser gravitation, lost them.

It was maintained that while the planets were still in a hot state, with a consequent very rapid motion of the gas atoms, the lighter (and therefore more mobile) atoms of hydrogen and helium succeeded in escaping from the terrestrial planets almost entirely, the atoms of the somewhat heavier elements only partially, while the atoms of medium and heavy elements were fully retained. When these planets cooled, the rocky substances (constituting the bulk of their mass) originated, whereas when the giant planets cooled, part of the hydrogen reacted with

* We do not mention helium and argon, since they are formed abundantly on Earth through the decay of radioactive elements. According to the latest data, however, neon, krypton and xenon are also formed in negligible quantities as by-products of radioactive breakup. Thus, all the inert gases were not initial constituents of the Earth; they originated later in the evolution of terrestrial matter.

other chemical elements to form such hydrogen-rich compounds as methane and ammonia.

Hence, the reason for the difference in the chemical composition of the planets was seen in the difference of their masses, in the difference of their gravitation which prevented the dissipation of the light gases. In recent years, this view has encountered two insuperable obstacles: first, the discovery of an atmosphere on Saturn's satellite, Titan, and, second, the theoretical investigation of the dissipation process.

In 1944, the American astronomer Kuiper discovered that Titan has a mighty atmosphere, composed of methane and, apparently, ammonia. Titan is a small body—its mass is 40 times less than that of the Earth. Its gravitation is slight and even in a cold state, let alone in a hot one, is incapable of retaining hydrogen. What is more, even methane, which is eight times heavier than hydrogen, is hardly retained at present by Titan, though its temperature, due to its great distance from the Sun, is very low (about —150°C). Methane would quickly dissipate into space if the temperature of Titan's surface rose 100 or 150°, i.e., to 0°C.

Discovery of a methane-ammonia atmosphere on Titan has shown that the presence of such atmospheres on the giant planets has nothing to do with their large mass and that there are bodies in the solar system which never were in a hot state.

The view persisted for years that at high temperatures the dissipation of the light gases from gaseous masses must have proceeded at a sufficiently fast pace, and that this might be the reason for the different composition of the two groups of planets. In 1951, Shklovsky established that the early conclusions had been based on a wrong application to gaseous masses of formulae related to another case of gas dissipation, that of the dissipation of an atmosphere under gravitation of the solid body of a planet. In the case of a gaseous mass held together by its

own gravitational force, there would either be the dissipation of the whole mass, without sorting the gases according to atomic weight, or the process would be so slow that, for the light elements to disperse and the heavier to remain, a period hundreds of times greater than the age of the solar system would have been required.

With knowledge of the solar composition one can compute how much hydrogen, helium and other light elements should be added to the Earth's substance to make it similar to the Sun's substance. The addition would have to be several dozen times the mass of the Earth as it is today,* i.e., the gaseous agglomeration would have to be more massive than Uranus and Neptune. But these planets, as is known, have not lost the light gases—they retain them in enormous quantities.

Despite these very serious objections to the idea that the difference in mass and chemical composition of the planets is the result of the dissipation of gases, it, as already noted, is still current in modern cosmogonic theories (Kuiper, Fesenkov). Kuiper, for instance, claims that the condensation which gave rise to Jupiter ("proto-Jupiter") was three times as massive as Jupiter is now, while "proto-Earth" was 120 times more massive than the Earth of today. True, in recent years Kuiper has altered his views somewhat, admitting that more and more types of bodies in the solar system formed via accumulation of cold matter.

The vast difference in the Earth's oxygen and nitrogen content, mentioned above, and the enormous dearth of inert gases show that not dissipation, but quite different causes conditioned the Earth's composition. Oxygen and nitrogen have almost the same atomic weight and should, therefore, dissipate with almost the same speed. If the nitrogen deficit can be explained by dissipation, then there

* According to the latest data, hydrogen and helium comprise 98 per cent of the solar substance (in mass), all other elements accounting for only 2 per cent.

would be little left of oxygen. Krypton and xenon atoms are much heavier than the molecules of water, oxygen and nitrogen. Were rapid dissipation possible, these lighter gases would have dissipated much earlier than krypton and xenon. And yet the Earth has them in great quantities, whereas the shortage of krypton and xenon is colossal. These characteristics of the Earth's composition result from its being formed of solid bodies and particles, of substances, which, under the temperatures prevailing at the Earth's distance from the Sun, must be in a solid and not gaseous state. It can be shown that the peculiar features of the other planets and their satellites were also conditioned by the temperatures at the time of their formation.

The densities of the terrestrial planets range between 3.9 gr/cm³ for Mars and 5.5 gr/cm³ for the Earth (see Table 1). The density of the Moon, also formed from the substance of the cloud's inner zone, is 3.3 gr/cm³. Were we to arrange these bodies in the order of their mass, we would see that for the Moon, Mars, Venus and the Earth, there is a regular growth of the mean density (3.3, 3.9, 5.1 and 5.52), except for Mercury, which, although half the mass of Mars, is almost of the same density as the Earth, although the latter is 18 times more massive.

Calculations based on current conceptions of the nature of the Earth's solid core (see pp. 78-79) show that the Moon, Mars, Venus and the Earth have the same chemical composition, and an unequal average density is due to differences in interior pressure. The larger the body, the greater its gravitation, and the greater the pressure of the outer layers on the interior, compressing the substances there to a high density. As for Mercury, it consists of a heavier substance. It is the planet nearest the Sun and, because of this, it was formed of strongly heated solid particles which retained only the most refractory substances. The more refractory substances are usually the heavier ones.

It is worth noting that bodies consisting of rocky matter, heavier even than the Earth's substance in an uncompressed state, are found also in the zone of the remote planets. These are Jupiter's two satellites, Io and Europa.

Jupiter's four main satellites, discovered by Galileo have essentially different densities* (Table 5). The difference in density is in no way connected with the difference in mass of the satellites, which in any case are too small for their internal pressure to essentially affect density of the substance. The difference is connected with the distance of the satellites from Jupiter—the nearer the satellite to the primary, the greater its density. Io and Europa, the two satellites nearest to Jupiter, have a greater density than the Moon. But while the Moon is made of the same substance as the Earth, these satellites are composed of a heavier substance, though not so heavy as that of Mercury. The slight density of Jupiter's remote satellites—Ganymede and Callisto—shows that rocky substances comprise less than half their mass. The remainder of the substance must be light, similar, for instance, to solid carbonic dioxide.

*Table 5*

**Density of Jupiter's Main Satellites**

| Name of satellite | Distance from Jupiter (Jupiter's radius = 1) | Mass (Earth's mass = 1) | Density in gr/cm³ |
|---|---|---|---|
| Io . . . . . . . . . . . . . | 5.9 | 0.0121 | 4.03 |
| Europa . . . . . . . . . | 9.4 | 0.0079 | 3.78 |
| Ganymede . . . . . . . | 15.0 | 0.0264 | 2.35 |
| Callisto . . . . . . . . . | 26.4 | 0.0162 | 2.06 |
| Moon | | 0.0123 | 3.33 |

These data on the densities and composition of Jupiter's satellites show that Jupiter's surface was hot when the satellites originated. As we have seen, the Sun's radia-

* The densities of Jupiter's other eight satellites are unknown.

tion varied the temperature in the inner and outer parts of the initial solar-disc nebula, thus dividing the planets into two groups. Jupiter's radiation produced a similar effect. The heat in the inner part of the swarm of particles surrounding Jupiter was greater than in the outer parts, resulting in a zonal differentiation in the chemical composition of the particles, leading in turn to differences in the composition of the satellites. What is more, just as the remote planets, which are composed of volatile as well as rocky substances, proved to be much more massive than the rocky terrestrial planets, so with Jupiter—the mass of the two remoter satellites is greater than that of the two that are nearer.

At present, Jupiter's visible surface, i.e., the surface of the layer of clouds floating in its atmosphere, is cold. Jupiter's interior may be hot, but the heat flux from the interior to the surface is so negligible that it cannot be measured. The high temperature which prevailed in Jupiter at the time its satellites orginated is connected with its enormous mass. Even when its mass was half what it is now, Jupiter exerted a powerful attraction on the particles and bodies that fell on it. They plunged into its upper layers at terrific speed and the transformation of their kinetic energy into heat gave rise to considerable warmth. The high densities of Jupiter's nearer satellites and the diminishing of their densities the farther away they are, constitute an after-effect of this warming up, which has remained to this day.

The giant planets also vary in density (see Table 1). By comparing their density and mass, we can see without calculations that the difference in density is caused by different chemical composition. Jupiter and Saturn are far more massive than Uranus and Neptune, hence their inner pressure is greater than in Uranus and Neptune. At the same time, the density of Jupiter and Saturn is less than that of Uranus and Neptune; hence they are made of a lighter substance.

Uranus and Neptune have practically the same mass, but Neptune has a noticeably greater density than Uranus; it follows, therefore, that Neptune's substance is heavier than that of Uranus. In comparing Jupiter and Saturn, we see that Saturn's lesser density can be explained by its smaller mass and lesser internal pressure, so that without special calculations one cannot know whether the two planets are of the same or different composition.

With a knowledge of the compressibility of different substances under high pressure, we can calculate the dimensions a sphere of this substance might have, were it of a quantity equal to Jupiter's mass. All substances, save hydrogen, will produce spheres smaller in size than Jupiter and only hydrogen, Nature's lightest substance, will produce a somewhat larger sphere. This means that Jupiter consists of hydrogen with an admixture of heavier chemical elements.

Laboratory investigation of the behaviour of different substances has been conducted only under pressures up to 100,000 or 200,000 atmospheres. But at the centre of Jupiter and the other planets, the pressures are of the order of many millions of atmospheres and, therefore, in studying the internal structure and composition of the giant planets, we must resort to theoretical computations of the compressibility of hydrogen and other substances. Under pressures of tens and hundreds of millions of atmospheres, the atoms' electronic shells are completely "crushed." The compressibility of substances in such conditions can be computed with adequate accuracy. But under pressures of a few million atmospheres, the atoms' electronic shells are only deformed, and not destroyed, which makes theoretical computation of compressibility exceedingly difficult and unreliable.

Calculations show that Jupiter must have not less than 50 and perhaps 85 per cent hydrogen content. As to Saturn, similar calculations showed it to have somewhat

less hydrogen (not more than 75 per cent), and somewhat more of the heavier elements. Nevertheless, due to its smaller mass and lower internal pressure, Saturn's density is less than that of Jupiter. If we turn to Uranus and Neptune, the hydrogen content continues to diminish, while that of the heavier elements increases.

If we omit the difference in composition between Uranus and Neptune, we would get the impression that hydrogen content increases with the planet's mass. But if we take this difference into consideration, we shall plainly see that the reason is not so much the planet's mass as its distance from the Sun.

The greater the distance of a planet from the Sun, the greater is the circumference of the belt of the gas-dust cloud (disc), along which the planet's substance was originally distributed, and the greater the width of this belt (we recall that the distance between the neighbouring planetary orbits increases the farther they are from the Sun). From Jupiter's zone to that of Neptune the space density of the cloud dropped consequently with the speed of the cloud's evolution, of planetary formation, diminishing.

Hydrogen could freeze to the hard particles only when their temperature was below —270°C, i.e., only when the inner region of the dust disc had fully blocked the Sun's rays to the zone of the giant planets. As numerous asteroid bodies took shape in the zone of the terrestrial planets, so did the interior of the disc become more and more transparent.

When the Sun's rays penetrated to the part far away from the Sun, the hydrogen evaporated fully from the dust particles and the smaller fragments and partly from the surface of relatively large "embryos." In these conditions, the somewhat later formation of the remoter giant planets (compared with those closer) entailed a progressive decrease in the hydrogen content from Jupiter to Neptune.

## 6. ASTEROIDS, METEORITES AND COMETS

Corresponding to the two planetary groups formed from the proto-planetary cloud's inner and outer zones of different chemical composition are two other groups of the smaller bodies of the solar system. As we have seen in the chapter "Academician Schmidt's Theory of Planetary Formation," a feature of the period of transition from the first to the second stages of the dust disc's evolution was the formation and disintegration of numerous intermediate bodies, and the accumulation of new bodies from the fragments. The asteroids, meteorites and comets are the remnants of these bodies. But whereas asteroids and meteorites relate to the inner zone of the cloud, the zone heated by the Sun, and consist therefore of rock substances, the comets take shape in the zone of the giant planets, and their cores are composed chiefly of frozen gases.

There is a whole belt of asteroids in the wide gap between the orbits of Mars and Jupiter on the demarcation line between the terrestrial and giant planets. Some of them travel along elongated paths and enter the zone of the terrestrial planets, as, for instance, the asteroids Amor and Adonis; others, the zone of the distant planets, as, for instance, the asteroid Hidalgo, but the bulk of the asteroids never go beyond the confines of this gap (Fig. 14).

The asteroids range from bodies hundreds of miles in diameter to less than a mile, the smallest ones coming closer and closer to what is known as meteoric bodies.

The smaller the asteroids, and also meteor bodies, the more there are of them. Since meteor bodies are small, they are not visible in interplanetary space; we see them only when they collide with the Earth, viz., dive into its atmosphere and, heating up and disintegrating, produce the flash of the "shooting star." The remnants of the larger meteor bodies, which had diameters of dozens of centimetres and even of several metres and entered the Earth's atmosphere at the relatively low speed of 9-12 miles per

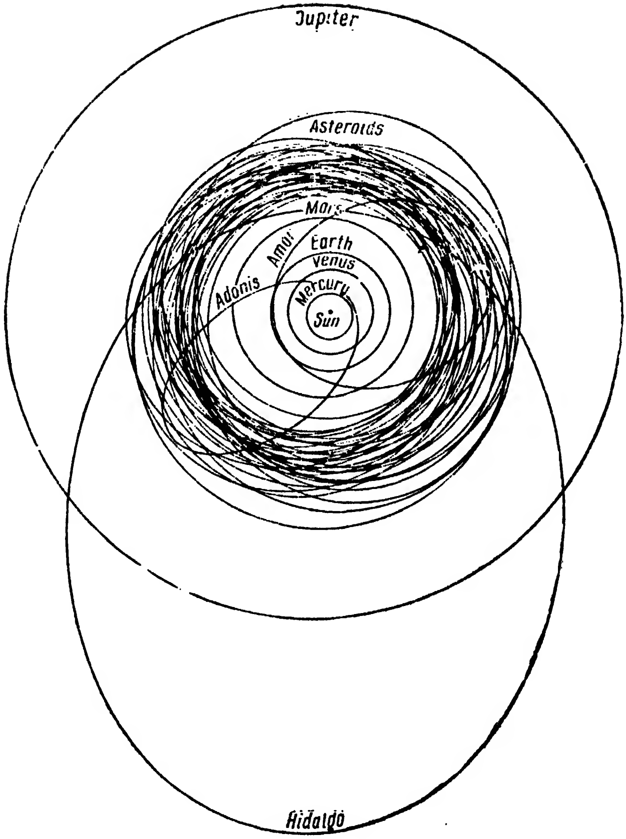



*Fig. 14.* Asteroid orbits

second, sometimes reach the Earth in the form of meteorites, thus enabling us to study their peculiar structure and chemical composition. The fragmentary structure of numerous meteorites graphically shows that their substance has passed again and again through processes of disintegration and agglomeration (Fig. 15).

It has been suggested that the asteroids and meteorites had their origin in the explosion of a large planet that once moved between the orbits of Mars and Jupiter, but no physical explanation of the explosion has been offered. Furthermore, this hypothesis does not explain the variety in the asteroids' orbits and the meteorites' structural characteristics.

According to Schmidt's theory the substance of the asteroids and meteorites never constituted one single body. The dust disc gave rise to many bodies of the size of large asteroids. During the period of transition (from the first stage of evolution to the second), the fragments of asteroidal bodies, splintered in collisions, could, together with the primordial particles, form new bodies, which

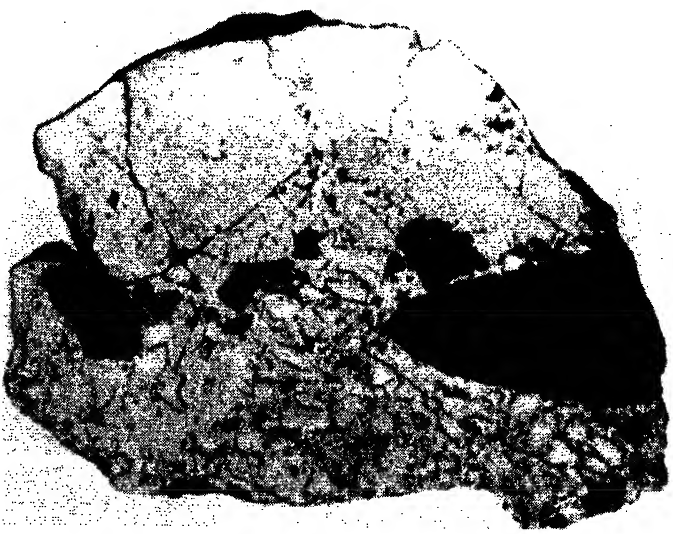


*Fig. 15.* A meteorite with a fragmentary structure

thus acquired a fragmentary structure. But later, when the bulk of the substance had gone into the intermediate (asteroidal) bodies, formation of new bodies ceased, while destruction from collisions continued. Furthermore, they diminished in number as they joined the planetary "embryos." Whereas there are no bodies of the asteroid type left inside the zone of the terrestrial planets (between their orbits), there are still several thousand on its outer fringe, between the orbits of Mars and Jupiter. But only 60-70 asteroids in all have a diameter of more than 60 miles. The collisions of asteroids with one another and with meteoric bodies lead to their gradual disintegration —reduced dimensions and the decrease in the total of large bodies.

Meteorites are asteroid fragments that are not completely destroyed when they dive through the Earth's atmosphere. Their thorough laboratory investigation upon being found yields very valuable information about their substance tending to confirm the above picture. For example, after studying the isotope composition of several elements extracted from meteorites, Academician Vinogradov concluded that meteorites had never been part of a large planet.

The small asteroidal fragments do not accumulate in interplanetary space, but fall continually on to the Sun, due to the pressure effect of sunlight radiation.

Radiation pressure acts on an immobile particle strictly radially and only somewhat weakens the Sun's attraction. For very small particles, of about 0.0005 mm in size, the radiation repulsion may even exceed attraction.

The matter is more complicated when we have particles moving around the Sun along circular orbits. The Sun's rays fall slightly in front of these particles, due to light aberrations. Therefore, along with the force of repulsion there appears a force directed against the particle's motion, i.e., a force retarding its motion (Fig. 16). Due to retardation, known as the Pointing-Robertson effect, the particle gradu-

ally draws nearer the Sun, moving spirally, evaporates in its heat, and eventually its substance joins to the Sun in the form of a small vapour cloud.*

It was presumed a few years back that due to the Pointing-Robertson effect much of the substance of the primordial cloud's inner zone fell on to the Sun. The particles joining with the Sun participated in the cloud's rotation, and it was therefore considered that they tended to make the Sun rotate, as it does today, in the same direction. However, calculations carried out by V. S. Safronov in 1955 proved that the fall-out of matter due to the Pointing-Robertson effect was relatively small and, thus, could not affect the Sun's rotation.

In our day, as mentioned earlier, radiative retarda-

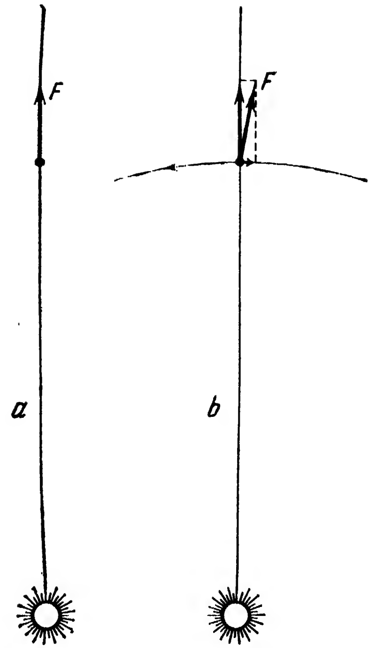



*Fig. 16.* Radiation pressure of a sun ray on an immobile particle (*a*) and on a moving particle (*b*). In the second case, force (*F*) has a component directed against the particle's movement

* As V. V. Radzievsky showed in 1950, the Sun's rays produce an analogous effect also on particles moving around a planet, compelling them to close up with the planet and fall on its surface. The nearer the planet is to the Sun the quicker this process. This is probably one of the main reasons why Mercury and Venus, the planets nearest to the Sun, have no satellites. Apparently, the particles that circled around them during their formation process fell on to their surface before they could accumulate into a large stable satellite.

tion prevents accumulation of small asteroid fragments, compels them to approach the Sun along a spiral path and accede to it. The smaller the particle, the faster is its approach to the Sun, taking, astronomically speaking, short periods of some 100 million years for a body 1 cm in diameter and some 10 million years for a body of 1 mm in diameter to reach the Sun's immediate vicinity

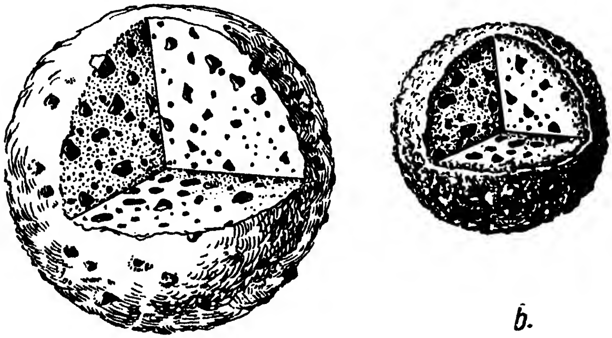


*Fig. 17.* Structure of a comet's "ice" nucleus: *a*) The nucleus of a comet which has not approached the Sun. *b*) The nucleus of a comet after several approaches to the Sun

from the asteroid belt. The rarefied swarm of particles approaching the Sun reflects and diffuses sunlight and, as such, is one of the main sources of the faint glow known as the Zodiacal Light.

Modern telescopes do not permit observation of such small bodies as asteroids if farther from the Sun than Jupiter's orbit. Therefore of the small bodies that originated in the zone of the giant planets and still exist, we can observe only those moving along elongated orbits and even then only those whose perihelion (the point in the orbit nearest the Sun) is not more than two or three A. U. away from the Sun. These are the comets.

Until recently, most astronomers believed the comet's nucleus to be a dense swarm of discrete particles. It was known that the comet's nucleus could not be an immense rarefied swarm, since it does not fall apart, in its approach to the Sun, under the latter's tidal forces. But in maintaining the comet's nucleus to be a dense swarm, investigators ignored the fact that in such swarms there are bound to be collisions between the particles, with the transformation of mechanical energy into heat. This, in turn, as A. D. Dubyago pointed out, leads to the swarm's rapid shrinkage and conversion into a solid body. It is precisely these solid bodies, composed of frozen gases with a small admixture of rock particles, that constitute the comet's nucleus (Fig. 17), usually ranging in diameter from several hundred metres to several kilometers. These are, in their way, huge "lumps" of snow and ice (not only of water but of various other substances), "contaminated" with rock admixtures.

According to the Dutch astronomer Oort, the Sun is surrounded now by a huge swarm of comets, a thousand times larger in diameter than the planetary system. Thousands of millions of comets in this swarm are inaccessible to modern methods of observation since they never enter the inner parts of the planetary system. Their paths are such that even the perihelia are far removed from the Sun. Not, therefore, warmed by its rays, they have preserved intact their store of frozen gases throughout thousands of millions of years. We say thousands of millions because the comet swarm originated at the time of planet formation, which, as we now know (see "The Age of the Earth") took place some 5,000 million years ago.

Schmidt's cosmogonic theory helps explain the origin of the comet swarm discovered by Oort. It was a by-product of the formation process of the giant planets. Due to the low temperatures in the part of the dust disc farther removed from the Sun, the intermediate bodies formed in this zone were comprised mainly of frozen gases—the same composition observed at present in cometary nuclei. Attrac-

*Fig. 18.* A photograph of Morehouse's comet. 1908

tion rapidly decreases as distance increases. The Sun's pull is weak in the zone of the giant planets. Hence, even before they acquired their present masses, Jupiter, Saturn, Uranus and Neptune possessed a pull strong enough drastically to alter the orbits of smaller bodies flying past. Towards the end of the formation process of the giant planets, their masses had become already great, but, at the same time, there was still a host of intermediate bodies and their splinters flying around these planets. The pull of the slightly "incomplete" Jupiter, Saturn, Uranus and Neptune often ejected these bodies and splinters way outside the planetary system. Some, overcoming the Sun's attraction, broke away entirely, while others formed the giant swarm of comets from which the comets we now see, come.

The comet's ice nuclei, containing methane, ammonia, water, carbon dioxide and kindred molecules, approximate in chemical composition the distant planets, both having originated from one and the same part, remote from the Sun, of the original cloud.

The comets in this swarm constantly change their orbits under the attraction of neighbouring stars. Sometimes the stars impel a comet to break away from the Sun. Hence, the total number in the swarm is gradually decreasing. If the changed orbit brings the comet within the Sun's vicinity, its core begins to emit gases and we observe the comet moving at an exceedingly elongated, well-nigh parabolic path.

When they reach the neighbourhood of planets, comets are attracted by them and their orbits again change somewhat. If the orbit contracts, the comet reverts to the Sun more often. Its orbit changes again and again owing to planetary attraction, while the comet itself loses more and more of its gases due to the Sun's warmth.

The orbit changes in a pronounced way when the comet draws near the massive Jupiter. All the short-period comets making up the so-called Jovian family acquired their present orbits as a result of their close approach to it.

The short-period comets disintegrate comparatively quickly, due to the intensive evaporation of gases from their nuclei. But when the outer layers of the comet's ice nucleus evaporate, the rock admixtures in the ice are partially drawn off with the gases, the remainder staying on the nuclei's surface to form a protective layer preventing further rapid evaporation (Fig. 17, *b*). Hence there are short-period comets, for instance Encke's comet, that have survived dozens of approaches to the Sun.

The particles that leave the comet's nucleus travel in a stream almost parallel to its orbit. Meteor showers, sometimes very intensive, are to be observed when the Earth encounters such a swarm of particles.

## 7. THE INTERNAL CONSTITUTION OF THE EARTH

The first concepts of the Earth's inner structure originated more than 20 centuries ago when scientific knowledge was too immature to allow a correct approach to this problem. Greece was one of the centres of science in ancient times. In the mountains of Greece there are many water-flushed caves and rivers now flowing under the ground, now on the surface. Observation of the natural environment led Greek scientists to the belief that the bowels of the Earth were hollows through which water, air and fire circulated. This primitive view, which ascribed the structural charac-

teristics of a small country to the entire globe, persisted, with only minor alterations, for more than 2,000 years.

Only 200 years ago the French scientist Bouguer measured mountain gravitation for the first time and concluded that the Earth's interior must be much denser than mountain matter. It was found through further measurements that the Earth consists of a substance, which, on the average, is roughly five times heavier than water. And so it was proved that our planet is neither a hollow, nor a body filled with water.

A comparison between the Earth's mean density and that of its surface layers, and also measurement of the globe's oblateness confirmed that density of the Earth increases the closer to its core. Discovery of this fact greatly influenced the further development of views on the globe's inner structure.

A study of rocks, many of which originated due to the solidification of molten matter, and observation of volcanic eruptions when molten lava emerges on to the Earth's surface, led the geologists of the late 18th century to conclude that the Earth's inner heat was of enormous importance. Thus, when Laplace postulated in his cosmogonic hypothesis that the Earth originated from an agglomeration of hot gases, the concept of the Earth as a body gradually cooling downwards from the surface, with its original heat intact inside, gained widespread recognition. In the early 19th century, most scientists maintained that the solid crust was from 30 to 60 miles thick, with a molten core below.

The year 1839 saw the publication in St. Petersburg of D. Sokolov's *Course in Geognosy*, in which he wrote, "In making geognostic facts conform to . . . mathematical facts,* we must, it seems, agree that our Earth is a spherical body,

* Here D. Sokolov meant geological data and the results of mathematical investigation of the flattening of rotating liquid bodies with different internal density distribution, proving that density is greater the closer to the Earth's centre.

consisting of a solid crust and a hot liquid core; in this core, or better, in the globe's molten interior, the minerals are distributed according to their relative weight, so that right in the middle there are metals with rock around them... in the metal layers iron plays the main role as the most abundant metal in nature.... The globe's interior is therefore visualized as the hearth of a smelting furnace, with the metals always at the bottom and the slag at the top."

Thus in the past century there originated a concept of the Earth's internal structure, which prevailed until very recent times.

* * *

The erroneous view that the Earth's inner heat implied an original molten state was frequently emphasized by Academician V. I. Vernadsky many years ago. He wrote: "...Atomic radioactive heat, and not the residue heat of the cooling planet, as was believed until quite recently, is the main source of the heat which explains all the geological processes taking place on the Earth.... Earlier this heat was explained by cosmogonic hypotheses about a once molten planet, which, unfortunately, are still taught in our schools."

According to Academician Schmidt's theory, the Earth, which gradually came into being through agglomeration of solid particles, never passed through a molten stage. The high temperatures inside the Earth are due mainly to the accumulation of heat released through the breakdown of radioactive elements and only slightly to the heat released in its formation process.

The Earth's size was increased by the fall-out of asteroid bodies and their splinters on to its surface. In this process the kinetic energy of the particles was transformed into heat. According as heat was generated on the surface, most of it escaped into space, but only a small portion went to warm up the upper layer. At first, the warming-up process grew with the increase in the Earth's mass, while its gravitational

attraction simultaneously increased the force of impact. Thereafter, according as the matter dwindled and the process of growth slackened, the warming-up process faded. According to V. S. Safronov's calculations, the layers currently at a depth of some 1,500 miles should have reached the maximum temperature, but not more than 100°C. The Earth's heating up is wholly due to radioactive elements.

The Earth's substance contains a small admixture of radioactive elements: uranium, thorium, radium and potassium.* The atomic nuclei of these elements disintegrate continually, becoming the nuclei of other chemical elements. In the disintegration each uranium or thorium atom is transformed, comparatively quickly, into a whole series of intermediary radioactive atoms (radium atoms, in particular) eventually becoming a stable atom of one or another lead isotope** and several atoms of helium. Calcium and argon originate in the disintegration of potassium.

Thermal energy is generated in the process of disintegration of radioactive elements. From the separate particles this heat easily escapes outwards and dissipates in space. But when the Earth, a body of enormous dimensions, took shape, thermal energy began to accumulate in its interior. Although in a unit of time, such as one year, very little energy is generated in each gramme of the Earth's substance nevertheless, in the thousands of millions of years of the Earth's existence, so much has been accumulated that it has raised the temperature in its interior to several thousand degrees. According to Y. A. Lyubimova'a calculations, the Earth's surface layers, from which the heat can escape slowly, have probably already passed the heat peak and are now cooling off, but deep in the interior of the Earth the heating process apparently still continues. This storing of thermal energy in the interior in no way influences the Earth's

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* Not all potassium atoms are radioactive, but only those with the atomic weight of 40.

** *Isotopes* are atoms of one and the same element varying solely in atomic weight.

surface and the conditions of life on it, because surface temperature is conditioned not by the inner heat, but by that received from the Sun. Since the Earth is a bad thermal conductor, the heat flux from the Earth's interior to the surface is 5,000 times less than the heat flux from the Sun.

The Sun's substance also contains a small quantity of radioactive elements, but the energy they generate is quite negligible as compared with its powerful radiation. In the Sun's interior, pressure and temperature are so high that thermo-nuclear reactions are constantly taking place, with the continuous transformation of atomic nuclei of hydrogen into more complex atomic nuclei of helium; in this process, vast quantities of nuclear energy are liberated—the energy that maintains solar radiation for thousands of millions of years.

The origin of the atmosphere and hydrosphere* is, apparently, closely linked with the process of heat generation in the Earth. Water and gases made their appearance on the Earth together with the solid particles and bodies of which it is formed. Although the temperature of the particles in the zone of the terrestrial planets was too high for gases to freeze to them, nevertheless, in these conditions gas molecules also adhered abundantly to their surface. Together with these particles, they entered into the composition of larger bodies, and afterwards of the Earth itself. Furthermore, as Academician Schmidt noted, icy bodies from the remote planetary zone must penetrate into the zone of the terrestrial planets (an analogous process is under way even now—comets approaching the Sun; as described above, these comets have "ice" cores). Prior to becoming heated and evaporating, they might have fallen out on to the Earth, imparting to it their water and gases.

Heating is the best method of expelling gases from solid bodies. Consequently, the Earth's heating-up process was

* The *hydrosphere* is what scientists call all the water enveloping the globe, as contained in the seas, oceans, rivers, lakes, the snow caps of mountain peaks and sub-soil water-bearing strata.

accompanied by emission of gas and water vapour of which there were small quantities in the Earth's rock substances. Having made its way to the surface, the vapour condensed into the water of the seas and oceans, while the gases formed the atmosphere, with an original composition differing substantially from that of the present day. The present composition of the Earth's atmosphere is largely conditioned by the plant and animal life on the Earth's surface.

Emission of gas and water vapour from the Earth's interior continues to this day. During volcanic eruptions, large quantities of water vapour and carbon dioxide are ejected into the atmosphere, while combustible gases leak from the Earth's interior in different places.

* * *

The question of how the new theory of the Earth's origin has affected that of the origin of life on the Earth, as elaborated by Academician Oparin, is of considerable interest. According to Oparin's theory, life arose in the process of the gradual growth in complexity from simple organic compounds (such as methane and formaldehyde) which were in a dissolved state in the water on the Earth's surface. In his theory Oparin proceeded from the then widely held view of the Earth originating from hot gases and that it solidified after passing through a molten state. Methane could not have existed at the phase of a hot gas agglomeration. In tracing the formation of methane, Oparin conjectured its genesis as the result of the reaction of hot water vapour with carbides (metal-carbon compounds.) He held that methane together with water vapour found its way upward through cracks to the Earth's surface and thus appeared in a water solution. It should be borne in mind that only the formation of methane was regarded as having taken place under a high temperature, while the further process up to the origin of life took place already in water, i.e., at a temperature of less than 100° Centigrade.

According to Academician Schmidt's theory, gas and water vapour were present in small quantities in the Earth's composition from the very outset. Hence, water could have appeared on the Earth's surface in the early stages of our planet's evolution. Dissolved in it from the very beginning were the simplest hydrocarbons and other compounds. Thus, the new cosmogonic theory postulates the presence on Earth from its very inception of the conditions needed for the origination of life as envisaged by Oparin.

* * *

Investigation of the propagation of seismic waves carried out at the end of the 19th century revealed that all the way to very great depths the Earth's density increases smoothly, thereafter the increase is abrupt. Earlier views interpreted this as an indication of a sharply drawn division inside the Earth between rock and iron.

It has now been established that the border of the Earth's dense core is located at a depth of about 2,900 km. from the surface (Fig. 19). The core's diameter is above half the Earth's diameter, its mass is about a third of the Earth's mass.

A few years ago most geologists, geophysicists and geochemists held that the Earth's dense core consisted of nickel-iron, similar to that present in meteorites. It was maintained that the iron had shifted to the centre while the Earth was still in a molten state. But in 1939, V. N. Lodochnikov, geologist, pointed out that we could not take this hypothesis for granted, saying that we knew too little about the behaviour of substance under the enormous pressures inside the Earth caused by the tremendous weight of the above-lying strata. Lodochnikov held that along with smooth gradual changes in the substance's density and other properties of matter, the pressure increase was bound to produce abrupt changes.

In elaborating his theory Academician Schmidt conjectured that the iron core had its origin in the gravitational

differentiation of the Earth's substance that set in after its interior had become heated. Schmidt's conjecture came up against the obstacle of the extreme slowness of this process. Soon, however, the further development in the works of Ramsay and Bullen of Lodochnikov's views did away with

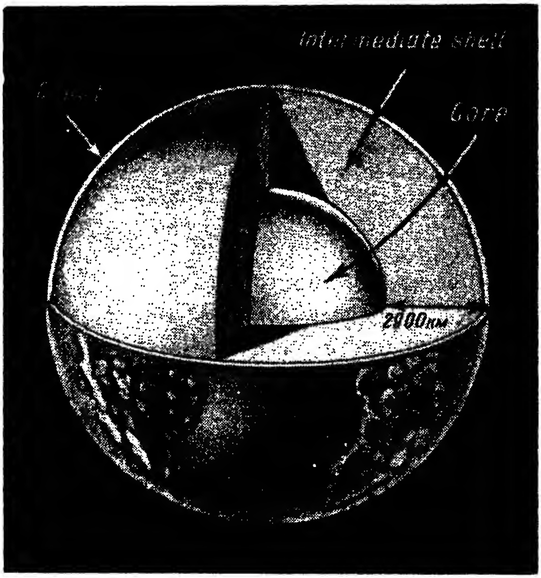


*Fig. 19.* Inner structure of the Earth

the need to explain the formation of the iron core. Abrupt change in the properties of a substance under extremely high pressure was corroborated by theoretical computations. The assumption that the Earth's dense core consisted not of iron but chiefly of rock substance which changed abruptly into a denser state under the pressure of 1,400,000 atm. (such being the pressure at the outer surface of the core) excellently explained all the available data concerning the Earth and the other bodies of the terrestrial group. (The conclusions pertaining to their composition, cited

earlier, on p. 58, were drawn on the basis of this concept of the Earth's core.)

Computations show that at a depth of some 160 miles, the pressure inside the Earth reaches 100,000 atm., and exceeds 3,000,000 atm. at the centre. Consequently, even at a

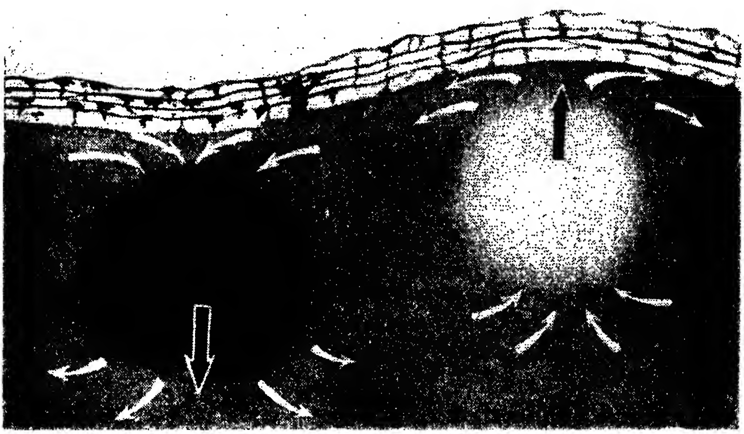

*Fig. 20.* Sinking of heavy and rising of light strata in the Earth's interior

temperature of several thousand degrees, the Earth's substance cannot be considered liquid in the usual sense, but amorphous like tar or pitch. Under the action of continuously acting forces, it changes slowly and becomes deformed. Thus, in rotating on its axis the Earth, because of centrifugal force, assumed a flattened form, as if it were liquid. At the same time, against temporarily acting forces it behaves like a solid, with elasticity greater than steel. This is manifested, for instance, in the propagation of seismic waves.

Due to the yielding nature of the Earth's interior there

occurs within it a slow movement of substances under gravitation: heavier substances sink to the centre, while lighter ones rise (Fig. 20). So slow is this stratification that, although it has been going on for thousands of millions of years, there is but slight concentration of the heavier substances towards the centre of the Earth. We can say that chemical stratification of the depths of the Earth has only just begun; it is now continuing beneath our feet.

Shifting of substances in the depths of the Earth is manifested on the surface by the rising and sinking of large areas of the Earth's crust; it is also manifested in the form of earthquakes. Earthquakes occur when huge accumulations of tension, due to the movement of substances, break out violently, causing parts of the Earth's surface to quake.

It was previously maintained that the Earth, after evolving from hot gas, cooled off very quickly and, after a brief molten state, became enveloped in a solid crust. With the further cooling of the Earth's interior, its volume decreased, and its crust, sinking on top of the contracting interior, folded, forming mountain ranges on the surface. Such was the so-called contraction hypothesis which appeared in the 30's of the last century. This hypothesis of mountain formation held sway for a long time. But after geologists made a better study of the Earth's crust, they perceived that a complicated interchange of rising and sinking is taking place in mountain areas, which the contraction hypothesis was unable to explain. Nevertheless, some geologists cling to this hypothesis down to this day.

The new theory of the Earth's origin, which postulates that the Earth has not cooled off but, on the contrary, has become heated, pictures the formation of the Earth's crust differently. The Earth's outermost layers, which we now observe, originated in the heating-up process of the Earth's interior, as a consequence of the lighter rocks rising to the surface (Fig. 21). This must have been a very long process, which in different parts of the globe probably took a different course.

The geo-chemist Goldsmidt and other scientists noted long ago that the substance of the Earth's crust could be melted out from the substances of meteorites. Academician Vinogradov confirmed this in a recent experiment when he partially melted a pulverized meteorite. A few years ago the Canadian geo-physicist Wilson conjectured from geological data that the Earth's crust had formed gradually.

*Fig. 21.* A cross-section of the Earth's crust

This is confirmed by measurement of the age of rock, indicating that central parts of the continents are older than the outer parts.

It can be expected that the new theory of the Earth's origin, which substantially alters our views on the pre-geological phase of its evolution, will help geologists to fathom the origin of its present external shape. It will help geologists to develop a theory on mountain formation, which will not only describe their complex past, but also reveal their cause and their connection with the motions of substances in the deep interior.

Volcanic processes, drawing their energy from the Earth's inner heat, are closely bound up with mountain formation. Independently of Schmidt's theory, geologists have begun to speak of late about the inner heat of the Earth, and not primordial heat. This is due to the growing understanding of the enormous role played in geological

processes by radioactive sources of heat. In the 70's of the last century Bredikhin realized that the present geological processes are connected with some kind of constant sources of energy, and not with the original heat.

This source of energy was discovered on the threshold of the 20th century in the form of radioactive elements. The new theory of the Earth's origin postulates yet another source of energy, that of heat generation caused by stratification of the Earth's interior under gravitation.* But it adds nothing new to the concrete picture of volcanic eruption.

## 8. THE AGE OF THE EARTH

The first attempt to transcend the biblical age of the Earth was essayed in the 18th century by the French naturalist Buffon, who based his hypothesis on the assumption that our planet had originated from a "droplet" of hot solar substance. After investigating the cooling of red-hot iron spheres, Buffon concluded that the Earth was approximately 70,000 years old.

It was only in the 19th century that geologists found a way of assessing the age of the Earth more accurately. By studying the speed of sedimentation at the bottom of seas and oceans, we can estimate the length of separate geological periods by measuring the thickness of the layers of sedimented rock. By evaluating the negligible quantities of salt carried to the seas and oceans by rivers, we can ascertain how long it took the salt now present in sea water to accumulate. As a result, geologists have established times of tens and hundreds of millions of years for the latest geological periods, and so the entire history of the Earth, its full age, must be still greater.

But the speed of sedimentation depends on many factors which cannot be calculated for the remote geological past.

* Stratification is an exceedingly slow process, hence generation of thermal energy is also very slow.

Consequently, the above-mentioned method of age determination furnished very unreliable results for extremely ancient rock.

Only in the 20th century, after radioactive elements were discovered and their disintegration studied, was the age-determination of different geological formations put on a solid basis. In recent years, the achievements of theoretical physics, on the one hand, and of cosmogony, on the other, have resulted in progress being made in investigating the age of the Earth itself. The decay of radioactive elements (uranium, thorium, potassium and others) may serve to gauge time because its speed is virtually constant everywhere. Not only the highest temperatures and pressures produced in our laboratories, but the temperatures and pressures prevalent in the depths of the Earth exert only a negligible influence on the speed of decay.

In natural conditions, wherever the radioactive element may be on the Earth, the proportion of its atoms that disintegrate in the course of one year will be constant everywhere. The decay of uranium, thorium and potassium is very slow, with only half the atoms disintegrating in the course of hundreds of millions and even in thousands of millions of years. Hence these elements still exist on the Earth, although it is clear that even at its formation they were only a very small part of its substance.

By measuring the number of radioactive atoms in any mineral and the number of atoms constituting the product of their decay, and knowing, moreover, the speed of decay, it is easy to compute the time needed to accumulate the quantity of decay products, i.e., we may gauge the age of the mineral.

Despite the seeming simplicity of this method of ascertaining the age of ores and minerals, its practical application is beset with numerous difficulties. To say nothing of having to measure negligible quantities of atoms, one must also choose a mineral specimen which has not actively interacted with the environment, which neither the radioac-

tive element nor the products of its decay have been added to or subtracted from. Finally, one must either be sure that at the moment of the mineral's formation there was no lead or any other decay-produced element in its initial composition or, if so, be able correctly to assess the initial quantity.

The difficulties are many, but when they are removed or overcome, the radioactive method furnishes the absolute age, without any additional hypotheses. Until recently the age of the oldest radioactive minerals so measured was believed to be from 2,000 to 2,500 million years. But in recent years minerals with a 3,000 million years' existence have been found.

The case is different when the investigated object was known to be not isolated from the environment in the period of time that interests us but, conversely, developed in active interaction with it. Here, too, a study of radioactive elements or their decay products helps to determine age, but the accuracy and correctness of the result achieved largely depends on the accuracy and correctness of the assumed evolution of the object under investigation on which the determination of age is based.

By studying the composition of lead from different deposits and measuring the quantities of both the lead isotopes existing in the Earth's substance from the very outset and appearing as a consequence of the disintegration of uranium and thorium, the British scientist Holmes concluded in the early 1940's that the Earth was 3,500 million years old.

A non-critical approach to Holmes' work led to his estimate of the Earth's age being accepted as reliable. Actually Holmes gauged the age not of the Earth, but of its crust, and in doing so he based himself on the outmoded conjecture of its originating from a red-hot mass of gases torn from the Sun. Holmes assumed that after the lapse of 15,000 years this had cooled off sufficiently to be enveloped in a solid crust, and so he maintained that the Earth's age was virtually the same as that of the crust.

In 1951-52, Academician A. P. Vinogradov carefully analyzed all the data and concluded that it was impossible to determine the age of the crust on the basis of data on lead alone. All that can be said is that it is not more than 5,000 million years.

The Earth as a whole is unquestionably older than its crust. But existing radioactive methods do not permit a direct determination of its age. What can be established is the age of the Earth's substance, i.e., we can establish how many thousands of millions of years have passed since the substance now comprising the Earth reached the state in which the formation of new radioactive atoms in the place of those disintegrated ceased. This can be done as follows:

There are two isotopes of uranium atoms, with the atomic weight of 235 and 238. Uranium-235 disintegrates much faster than uranium-238 and for this reason there is 139 times less of it on the Earth today. Theoretical physics entitles us to affirm that when uranium originated the atoms of the two isotopes were present in approximately equal quantities. In this case, knowing the speed of the disintegration of both isotopes, it is easy to compute the time needed for uranium-235 to become 139 times less than uranium-238. This proves that the age of uranium, and with it the age of the Earth's substance in general, ranges from 5,000 to 7,000 million years.

In 1946 Academician Schmidt, on the basis of his cosmogonic theory, roughly assessed the age of the Earth. He examined, rather, the speed at which the Earth's mass increased by accretion of matter from surrounding space. It was found that periods of the order of several thousand millions of years, deduced through radioactive ascertainment of age, were ample for the Earth to accumulate its present mass in this way.

At first, when there were still many particles in the cloud, the planets grew quickly, but as the stock of particles dwindled, the rate of growth diminished, so that today there is hardly any increase in the planetary masses. True,

there still is a fall-out of interplanetary matter on to the Earth now, in the form of meteorites and smaller meteoric bodies, which disintegrate and evaporate in the upper layers of the atmosphere. Hundreds of tons of meteoric substance fall out on to the Earth in a 24-hour cycle. But compared with the Earth's dimensions and mass, the quantity is absolutely negligible—it would take millions and millions of years to cover the Earth with a layer of meteorite dust 1 mm thick.

The bulk of the Earth's mass was formed of the solid substance originally dispersed throughout the Earth's zone of the proto-planetary cloud. The substance of this zone has long since become part of the Earth, while the left-overs have fallen out on to the Sun under the Pointing-Robertson effect. The meteor matter now falling out on to the Earth comes from regions farther away from the Sun. As mentioned above, meteorites come from the asteroid belt, while the meteor bodies resulting from the disintegration of comets come from still greater distances, viz., the zone of the giant planets.

All the data on the age of minerals, the Earth's crust, and the Earth's substance harmonize satisfactorily. In combination with Schmidt's cosmogonic theory, they present the following picture of the Earth's evolution.

Some 6,000 million years ago, the substance now constituting the Earth was in a state that favoured the formation of the atomic nuclei of radioactive elements. Later, in the matter of few hundred million years, this substance, after passing through a series of still inadequately studied phases, gave rise to the enormous gas-dust cloud surrounding the Sun, which was transformed, comparatively quickly, into a small number of large bodies—the planets, including our Earth.

Disintegration of the radioactive elements was accompanied by the release of heat. From tiny particles, the heat escaped into space, but when the particles formed a huge body—the Earth—the heat began to accumulate in its inte-

rior. Part of the interior substance began to melt some 4,000 million years ago.

The lighter molten substances were gradually forced to the surface where in the course of time they formed the Earth's crust composed of various rocks and minerals. This crust is changing all the time, its upper layers being washed away by streams of water and again sedimenting at sea and ocean bottom; the sedimented layers break up and form folds; new portions of the interior substance find their way to the crust all the time. Nevertheless, geologists have disclosed some ancient minerals of around 3,000 million years old, which have not undergone any essential changes in later geological processes.

The Earth's present stage of evolution might well be described as its maturity. Another few thousand million years will pass and the gradual cooling-off of its interior will entail the slowing down and fading away of the movements taking place in it.

Science still has a very hazy notion of the age that will be reached by the Earth, and what its very remote future will be like. Currently, scientists are chiefly concerned with studying the past, since it is imperative for the comprehension of the Earth's present state.

## CONCLUSION

Much still remains to be done to obtain a full picture of the origin of the solar system.

Some of the problems have not been examined at all, while others must be investigated in greater detail than hitherto. Why, for instance, has our Earth a satellite, the Moon, with a mass only 82 times less than that of the Earth itself, while other planets have satellites with masses thousands and millions of times smaller than their primaries? How did the Moon's surface take shape? Why has Mars no high mountains or mountain ranges? What was the origin of the chondrules, the tiny spheres, which are an important component of most meteorites?

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